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INFLUENCE OF TEMPERATURE ON CREEP, STRESS-RUPTURE, AND STATIC PROPERTIES OF MELAMINE-RESIN AND SILICONE-RESIN GLASS-FABRIC LAMINATES

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SUMMARY

Results of the following tests of melamine-resin glass-fabric laminates and silicone-resin glass-fabric laminates at temperatures up to 400° and 600° F, respectively, are reported: Static-tension, static-compression, tension-creep, and time-to-fracture tests.

The mechanical properties of both laminates weakened with increase in temperature, as a rule.

The creep data supply additional evidence that the percent increase in strain from one given time to another given time (called "creepocity") is independent of stress. An analysis of the creep data is represented by an equation which describes the effect of stress, time, and temperature. This equation is based on the activation-energy theory and a power function of time.

An analysis of the data shows the possibility that no creep will occur at temperatures below -10° F for the melamine-resin laminate and -119° F for the silicone-resin laminate.

INTRODUCTION

The series of tests reported herein is a part of a coordinated research program to investigate the mechanical properties of plastic laminates for use in aircraft construction. The purpose of this phase of the program was to determine the mechanical properties of two materials in a given range of temperatures, the higher temperatures being of particular interest. The reports of some previous investigations of the properties of plastics are given in references 1 to 8.

Melamine-resin and silicone-resin glass-fabric laminates were selected for study in the present investigation after an extensive survey by the Bureau of Standards (ref. 9) to determine which of several materials were most promising for high-temperature work. This study showed that at that time (1949) silicone- and melamine-resin laminates were outstanding.

This work was conducted in the Department of Theoretical and Applied Mechanics as a part of the work of the Engineering Experiment Station of the University of Illinois under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics. Credit is due the various organizations who prepared the laminates and provided information pertaining to the composition and manufacturing conditions of the two materials tested. These include the American Cyanamid Co., Dow Corning Corp., General Electric Co., and Taylor Fibre Co.

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SYMBOLS

d	distance through which shear stress acts in carrying unit of flow from normal to activated state
h	Planck constant, 6.624×10^{-27} erg-sec
k	Boltzmann constant, 1.3805×10^{-16} ergs/$^{\circ}$K
l	length of compression specimen
n	constant independent of stress, dimensionless
q	stress-concentration factor
R	gas constant, 1.986 cal/mole-$^{\circ}$K
r	radius of gyration of transverse cross section of compression specimen
T	absolute temperature, $^{\circ}$K
T_a	temperature below which material shows no time sensitivity

t	time, hr
t_o	constant conveniently taken equal to unity and having dimensions of time
α	constant presumably independent of material
ΔH	energy of activation, cal/mole
ΔS	entropy of activation, cal/mole-^oK
ϵ	total strain, in./in.
$\dot{\epsilon}$	creep rate, in./in-sec or in./in-hr
ϵ_o	time-independent strain, in./in.
ϵ_o'	coefficient of time, independent term, in./in.
λ, L, A	dimensions of "unit of flow"
σ	normal stress, dynes/sq cm or lb/sq in.
σ_o	constant in stress term, lb/sq in.
ϕ	creepocity

TYPES OF TESTS

The following tests were performed at various temperatures on each of the two glass-fabric laminates: Short-time static-tension and static-compression tests, creep tests of 500-hour duration with recovery data taken at the end of each test, and time-to-fracture tests in which the elapsed time between application of the load and fracture of the specimens was determined for various stresses.

From the static-tension and static-compression tests, the following properties were determined: Modulus of elasticity, yield strength, ultimate strength, and rate of strain. The following measurements were made from the creep data: The "elastic" strain at 20 seconds after loading, the total creep at 500 hours, the rate of creep at 500 hours, and the percent increase in strain at 500 hours. From the recovery data measurement was made of the recovery strain at 20 seconds. The recovery strain was compared with the 20-second elastic-strain measurement at the beginning of the test.

While it was desired to obtain time-to-fracture data between 2 and 200 hours, the behavior of the materials, particularly at high temperatures, made it difficult to obtain data within these limits.

The melamine-resin glass-fabric laminate was tested at 40° (restricted to creep tests), 77°, 130°, 250°, and 400° F and the silicone-resin glass-fabric laminate was tested at 77°, 250°, 425°, and 600° F. The relative humidity was maintained at 50 ± 2 percent for all tests at 77° F. The relative humidity was maintained at 50 ± 2 percent for tests at 40° and 130° F although the control was performed differently and was less accurate than at 77° F. No attempt was made to control the relative humidity above 130° F.

MATERIALS AND SPECIMENS

Materials

Two plastics were tested in this program: a melamine-resin glass-fabric laminate and a silicone-resin glass-fabric laminate. The details of manufacture and composition of each material appear in table I.

Specimens

Dimensions of specimens for each type of tests performed are illustrated in figure 1. All specimens were cut from the sheet of laminate with their longitudinal axes parallel to one another.

The tension specimens were machined on a shaper and the compression specimens of two different lengths were turned on a lathe. The dimensions are shown in figures 1(a) and 1(b). The 2-inch specimens were used to obtain stress-strain data in compression, while the 1-inch specimens were used to obtain the ultimate compressive strength.

Two types of creep and time-to-fracture specimens shown in figures 1(c) and 1(d) were used for temperatures in the 40° to 250° F range. The first type used (fig. 1(d)) was machined on a shaper in such a manner that the wide faces of the ends of the specimen which served as the gripping surfaces were perpendicular to the planes of lamination. This is shown in figure 1(d), section A-A, the shading being representative of the planes of laminations. This shape proved satisfactory for a small load on the specimen; however, for a large load there was a tendency for the specimen to fail prematurely at the enlarged sections where the specimen was gripped, since the load was not distributed evenly over the entire enlarged section of the specimen. The outer laminations of the enlarged ends of the specimen carried part of the load only as long as the resin bond could withstand the shear stresses between laminations. The grips did not offer any restraint to shearing since gripping forces were parallel to the planes of lamination.

Failure at the grips was overcome by changing the shape of the ends of the specimen as represented by figure 1(c). This new design was machined on a shaper with the gripping surfaces of the specimen parallel to the planes of lamination.

For temperatures between 400° and 600° F a different type of creep specimen was used to fit the high-temperature Baldwin creep machine. Specimens with threaded ends and a circular cross section (fig. 1(e)) were adopted after some preliminary work with a type having threaded ends and a rectangular cross section. The rectangular cross section was the same as that used in the low-temperature creep specimens. Both specimens were very difficult to machine but the one with the rectangular cross section was especially so. The specimen of circular cross section was used throughout, except where reference is made to the type with the rectangular cross section.

All specimens were kept in the air-conditioned laboratory for at least 2 weeks prior to the start of a test. The condition of this laboratory was maintained at a temperature of 77° ± 1° F and a relative humidity of 50 ± 2 percent throughout the entire testing program.

APPARATUS AND TEST PROCEDURE

Static-Tension Tests

Short-time tension tests were performed on specimens as shown in figure 1(a). These specimens were tested in tension on a 10,000-pound-capacity Olsen universal testing machine with beam weighing and equipped with a separate variable-speed drive. For tests at 77° F, the specimens were held in Templin wedge grips. A smaller set of grips specially prepared to fit in a tube furnace was used for high-temperature tests. The apparatus and specimens appear in figure 2. Some elasticity was required in these grips to prevent the specimen from slipping out of the grip. To accomplish this the cap screws shown in figure 2 were provided with shanks the same diameter as the root of the threads and were tightened nearly to the elastic limit.

The use of the tube furnace for the elevated-temperature tests necessitated special strain-measuring apparatus. For the tension tests C-shaped plates were provided with set screws to attach them to the specimen at the two ends of the specimen gage length. Each of these plates was clamped to a pair of rods which transferred their motion to another C-shaped plate below the grips and outside the tube furnace. A lever-and-dial type extensometer was attached to lugs on the two C-shaped plates located outside the furnace so as to indicate the displacement between these plates and hence the strain in the specimen.

In order to make it unnecessary for the specimen to support the weight of the extensometer and in order to prevent damage to the instrument if the specimen fractured while the extensometer was attached, the extensometer was suspended by means of a flexible coil spring such as shown in figure 2.

Since the rate of strain in a static tension test which is conducted at a constant rate of cross-head motion varies continuously during the test, it is necessary, for purposes of correlation, to establish some particular strain value at which to determine the rate of strain. In all of these tests the rate of strain during testing just below the proportional limit was used. A preliminary test was conducted for each laminate at each temperature to determine the rate of testing speed required to produce a rate of tensile strain of 0.0016 inch per inch per minute. This value was selected to correspond with previous tests (refs. 10 to 13). All succeeding tests were considered valid if the rate of strain just preceding the proportional limit was within the limits of 0.0016 ± 0.0003 inch per inch per minute. This rate of strain corresponds roughly to the rate of strain produced by testing machines operated at a head speed of 0.05 inch per minute. However, it should be noted that different machines and even different materials tested in the same machine at the same rate of cross-head motion will not in general produce the same rate of strain in the specimen. This is due to different relative stiffnesses of the machine, the specimen, and the auxiliary gripping apparatus. During the test, readings of load, deformation, and time were recorded up to a point within a few percent of the load at which failure was expected. The extensometer was removed before failure.

From these data the stress and strain were computed. Then diagrams of stress against strain and time against strain were plotted. The modulus of elasticity was determined in each case from the slope of the initial part of the stress-strain curve. The yield strengths at 0.05- and 0.2-percent offset were determined by constructing lines parallel to the initial part of the stress-strain curve and offset 0.05 and 0.2 percent, respectively.

An electrically heated tube furnace enclosed the tension specimen for tests in which the temperatures were greater than 77° F. Temperature control was maintained by hand adjustment of an auto-transformer controlling two heater elements in the furnace. The specimen temperature was determined by means of a thermocouple attached to the surface of the specimen at the center of the gage length.

A conditioning time of 15 to 20 minutes at testing temperature was employed before conducting the test.

Static-Compression Tests

Compression specimens were tested in the same machine as the static-tension specimens. Temperature-control apparatus was the same as described in the preceding section. Conditions of temperature and humidity were maintained the same for static-compression tests as for static-tension tests. Specimens tested at 77° F were tested using a compression tool as shown in figure 4 of reference 11.

Similar apparatus, which was better adapted to a tube furnace, was especially designed for tests at higher temperatures and is shown in figure 3. A slender compression tool held the specimen in the center of the furnace. This tool consisted of two hollow pistons in opposition inside a sleeve in such a way that a compression specimen could be loaded between the ends of the pistons. The upper piston was free to move vertically but guided by the sleeve to prevent lateral movement. The pistons were made hollow so as to minimize conduction of heat from the furnace. The specimen with C-shaped plates attached by set screws was inserted between the pistons through a rectangular slot in the sleeve. As in the tension tests at high temperatures two pairs of rods shown in figure 3 transferred the displacement of these C-shaped plates to the second pair of plates which was mounted below the furnace and below a bridge which carried the compression tool and the load applied to the specimen. A lever-type compressometer was attached to the lower plates as shown in figure 3 to indicate the strain of the specimen.

Two different shapes of specimens were required (fig. 1(b)), one to determine stress-strain relations and another to determine the compressive strengths. The 2-inch specimen ($l/r = 16$, where l/r is the ratio of the length of the specimen to the radius of gyration of the transverse cross section of the specimen) was used with the compressometer having a 1-inch gage length to determine the stress-strain relations. The 1-inch specimen ($l/r = 8$) was used in determining the compressive strength of the material to eliminate as far as possible the tendency for specimens to buckle. The rate of strain for the tests of 1-inch-long specimens was substantially the same as the rate of strain in the 2-inch specimens. This was accomplished by adjusting the speed of the testing machine so that the rate of increase in load during a test was substantially the same as the rate of increase in load corresponding to the proportional-limit load observed in the tests of the 2-inch specimens, for which the strain rates were known.

During the compression tests of the 2-inch specimens, readings of load, deformation, and time were recorded. From these data the stress and strain were computed and stress-strain and time-strain curves were plotted. The modulus of elasticity, yield strengths at 0.05- and 0.2-percent offset, and rate of strain were determined from these curves in the same manner as that described for the tension tests.

A conditioning time of 15 to 20 minutes was allowed at the testing temperature before each test.

Tension-Creep Tests

Tests at 40° F.- Two racks with creep equipment similar to the two used for room-temperature (77° F) tests, as described in the following section, were used for tests at 40° F. Instead of being exposed to controlled room conditions, however, the specimens were enclosed by insulated cabinets as shown in figure 4. Each cabinet consisted of a box lined with galvanized sheet steel and insulated with 4 inches of glass fiber. Cooling in the 40° F cabinet was accomplished by use of a eutectic-filled cold plate, which served as the evaporation chamber in a sulfur dioxide refrigeration system. The eutectic-filled cold plate was used in preference to open coils so that a temperature of 40° F could be employed without much disturbance of relative humidity in the cabinet by condensation on the cooling coils. The temperature was thermostatically controlled. A more detailed explanation of cabinet construction and temperature control is given in reference 14.

Tests at 77° F.- The equipment used for conducting the creep tests consisted of two steel racks from which 38 specimens could be suspended, calibrated weights and levers used for loading the specimens in tension, calibrated extensometers, a traveling microscope for measuring the strain indicated by the extensometer, and a clock equipped with a counter to record the elapsed time in hours. Figure 7 of reference 11 shows the creep rack with loading levers, specimens, extensometers, and auxiliary equipment. Figure 5 shows a specimen with creep-measuring equipment in place. In this figure, the specimen A was held by grips C which contained a hook-and-eye type of swivel joint B and C. This joint was provided in order to minimize the possibility of eccentric loading.

The extensometer used for measuring the creep consisted of a lever-type instrument with a traveling microscope D (fig. 5) for measuring the displacement between reference marks on the end of the lever E and a stationary arm F. The lever ratio was 10 to 1. One end of the lever was forked and fastened by pivots to the lower clamp attached to the specimen. The axis of this pivot passed through the centroid of the cross section of the specimen (the pin itself did not go through the specimen). Thus the strain measured by this instrument was the average strain in the specimen. The fulcrum of the lever was pivoted to a rod, the other end of which was fastened to the upper clamp on the specimen.

A spring clip G (fig. 5) was used to attach this rod to the upper clamp so that the extensometer could be left on the specimen, during fracture if necessary, without damage to the instrument.

The dials on the traveling microscope as well as the various extensometers were calibrated against a micrometer screw. Strains were measured to ±0.000001 inch per inch and were reproducible within ±0.000002 inch per inch. Flat clamps instead of pointed screws were used to attach the extensometer to the specimen because creep of the material might cause screws to sink into the specimen, thus causing early fracture. The distance between the centers of the flat clamps was considered to be the gage length of the extensometer. As used in these tests, this gage length was 10 inches. A track was provided for the microscope so that it could be moved from specimen to specimen quickly.

Tests at 130° and 250° F.- The cabinets used for 40° F tests were used also for 130° and 250° F tests. Each was heated with an electric strip heater which extended the full length of the cabinet. Temperature control was maintained by thermostats.

Creep-measurement equipment was identical to that used for the 40° and 77° F tests.

Tests at 400°, 425°, and 600° F.- The equipment used for high-temperature creep tests consisted of a Baldwin creep machine which was modified in several respects (see fig. 6). This machine consisted of a frame supporting a lever by which one specimen could be loaded, a furnace, and strain-measuring equipment. A temperature indicator and controller, as well as potentiometers and an autotransformer for adjusting furnace temperature distribution, controls for the strain-measuring instrument, and a clock were mounted on an auxiliary panel. A counterbalance, not shown in the figure, was fastened to the lever arm so that the small loads required for some tests could be accommodated. The counterbalance also made it possible to eliminate the consideration of tare weight in the calculation of the load necessary to produce the desired stress. Thermocouples were attached to the surface of the specimen at the middle and at the two ends of the gage length. Millivolt readings were measured by means of a precision potentiometer.

Creep-Test Procedure

Loads on all creep specimens at all temperatures were applied quickly but gently by means of a hydraulic jack. The zero time reading was taken as the time at which the total load was transferred from the descending jack to the specimen. The extensometer was read just before application of the load. Readings of extension and time were taken as soon after loading as was possible and at 30 seconds, 1, 2, 3, 5, 6, 7, 10, 12, 18, 24, 30, and 42 minutes, 1, 2, 3, 5, 7, 10, and 20 hours, and then every 24 to 500 hours. Following this the specimens were unloaded with recovery strain and time being recorded for 24 hours at the same intervals used on loading. This completed the test of a specimen.

Specimens at all temperatures were given a 24-hour conditioning period at temperature before loading.

Specimens for all stresses for each laminate at a given temperature were tested simultaneously wherever possible. The maximum stress employed in a creep-test series was determined from a preliminary creep test performed for each laminate. This test was started at a load which would produce a stress of about 60 percent of the tensile strength of the material. If the specimen did not fracture in 24 hours this load was increased about 6 percent of the tensile strength for the next 24 hours. This process was repeated until the specimen failed. A stress level of 80 percent of the highest stress which lasted 24 hours without failure was then used as the highest stress in the creep tests at each temperature.

Time-to-Fracture Tests

Time-to-fracture tests were conducted in a manner identical to the creep tests. The only difference was that stresses were obtained which were expected to cause failure within 2 to 200 hours after loading. Creep deflections and times were recorded for these tests also. The time of fracture was determined by a clock, which was stopped automatically by a switch attached to the loading lever when failure occurred. From these data, the relationship of stress and time-to-fracture was determined. Fracture stresses were based on the initial area of the specimen.

TEST RESULTS

Type of Fractures

Photographs of representative fractures of specimens tested in static tension and compression and tension creep are shown in figures 7 to 9. It was observed in the static tension and creep tests that as the temperature increased the fractures showed more and more of a ragged, fibrous appearance. At the higher temperatures the test section of the specimens swelled and delamination seemed to occur. At 600° F the silicone-resin laminate seemed to lose much of the resin binder and turned a darker brown.

The compression specimens fractured along planes which contained the transverse threads of the fabric and which were at an angle of about 17° to 31° to the longitudinal axis of the specimen, depending on the material and length of the specimen. For melamine resin the angle varied from 21° to 25° for 1-inch specimens and 17° to 20° for the 2-inch specimens. For the silicone resin the variation was 25° to 31° for the 1-inch specimens and 17° to 24° for the 2-inch specimens. The only pronounced change in angle due to temperature seemed to be from about 24° at 77°, 250°, and 425° F to an angle of 17° at 600° F for the 2-inch specimens of silicone-resin laminate.

Static-Tension Tests

Representative stress-strain curves for various temperatures and a time-strain curve for one temperature are shown for the two glass-fabric laminates in figures 10 and 11. From curves similar to these the following properties were measured: Modulus of elasticity (both primary and secondary),[1] yield strength at 0.05- and 0.2-percent offset, ultimate strength, and rate of strain. These properties are given in tables II and III with averages of similar tests.

For all tension tests it was desired to maintain a rate of strain approximately 0.0016 inch per inch per minute at the proportional limit. All tests which fell outside the limits of 0.0016 ± 0.0003 inch per inch per minute were excluded from those tests which were used to determine an average. See tables II and III.

Two curves are shown in figure 11 for the silicone-resin material at 600° F. In the test represented by the solid line the extensometer was attached to the specimen in such a way that the gage points were in contact with a surface whose plane was perpendicular to the planes of the laminations in the stress-strain curve. This was the usual manner of attaching the extensometer to the specimens and was satisfactory for most tests. However, it was observed that the specimen tended to bulge and delaminate near the end of the test. This suggested that the gage points might be slipping instead of remaining attached in the original position. Such action might account for the upward curvature observed in the stress-strain curve. This possibility was explored by testing a specimen to which the extensometer was attached with the gage points contacting the surface whose plane was parallel to the planes of laminations. The results are shown by the dashed line in figure 11.

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[1]The definition of modulus of elasticity in reference 11 is for the primary or initial tangent modulus. In the melamine resin a sudden change in slope of the stress-strain curve was noted after about 6,000 psi followed by a reasonably linear portion of the curve. The slope of this second linear portion was called the secondary modulus.

The first method of attaching the extensometer, while it seemingly did not have an effect on the first part of the test, apparently was the factor causing the concave upward trend in the 425° and 600° F tests of the silicone-resin material. Mounting the extensometer on the specimen by the second method mentioned eliminated possible slippage but may have caused the gage points to damage the outer laminations. No such difficulty was encountered with the melamine-resin material. It was noted that the difficulty mentioned apparently did not affect the yield-strength determinations for the silicone laminate as shown in figure 11.

In figures 10 and 11 each successive curve was displaced horizontally from its adjacent curve. The scale of the abscissa is correct as shown but the origin is correct for only the first curve.

Static-Compression Tests

Representative stress-strain curves for both materials at various temperatures and a time-strain curve for one temperature are shown in figures 12 and 13. From curves similar to these for the 2-inch specimens the following properties were determined: Modulus of elasticity (both primary and secondary), yield strength at 0.05- and 0.2-percent offset, ultimate strength, and rate of strain. Specimens 1 inch long were used to determine only the ultimate strength. Results and average values are given in tables IV and V.

In all tests except for the silicone-resin material at 77° F the average ultimate strength was higher for the 1-inch specimen than for the 2-inch specimen. The percentage difference in ultimate strength between the two different types of specimens increased with higher temperatures as shown in tables IV and V.

For all compression tests it was desired to maintain a rate of strain approximately 0.0016 inch per inch per minute at the proportional limit. All tests which fell outside the limits of 0.0016 ± 0.0003 inch per inch per minute (usually the first one of any series) were excluded from those tests which were used to determine an average. These are noted in tables IV and V.

In figures 12 and 13 each curve was displaced horizontally from the adjacent curves.

Tension-Creep Tests

Results of creep tests for each of the two materials at several temperatures and stresses are shown in figures 14 to 22. These data are shown plotted for the first 500 hours of creep followed by strain recovery curves for those specimens which were unloaded after 500 hours under load. The tests at 77° F were extended to greater lengths of time so that recovery data at 500 hours were not available. The differences in the two materials made it impractical to plot each set of data to the same scale. However, uniformity in scales was maintained wherever possible.

The relative humidity was maintained at 50 percent for tests at 77° F and for the first 3,200 hours of creep tests of the melamine-resin laminate at 40° and 130° F. The relative humidity of the test chamber was not controlled in the remainder of the creep tests.

In general the rate of creep was very large at the beginning of each test and continuously decreased as time progressed. The total creep at any given time and stress was greater at higher temperatures, and the total creep at any given time and temperature was greater for larger stresses.

The creep tests of both laminates at 250° F suffered from the fact that the temperature did not remain constant during the first part of the tests. For this reason tests at 15,000 and 30,000 psi for the melamine-resin and 4,000 and 8,000 psi for the silicone-resin laminate were repeated. The data were found to be in reasonably close agreement with those for the first tests.

In figure 22 is illustrated the type of creep curves obtained when the stress was increased at intervals. The increases were made in order to establish the approximate stress at which time-to-fracture creep tests should be performed. In the test shown in figure 22 the stress was increased from 8,000 to 9,000 to 10,000 and to 11,000 psi at which stress fracture occurred.

A control specimen was tested along with the creep specimens. These specimens were not loaded but strain readings were recorded in order to determine whether the material was stretching or shrinking because of factors other than creep.

The control specimens for the melamine-resin material showed very little change in length; no consistent trend was evident over the range of temperatures employed. The silicone-resin material on the other hand showed little change in length at the lower temperatures but increasing amounts of shrinkage as the temperature increased above 250° F.

It should be noted, however, that all the control specimens tested in the high-temperature creep machine were actually subjected to a stress of 150 psi. This was due to the weight of the lower gripping apparatus and extensometer. While a stress of 150 psi is small (compared with the stress of 4,000 psi present in the specimen of next higher stress) it may have affected the observed changes in length.

Difficulties were encountered at high temperatures which were not problems at low temperatures. In addition to the problem of maintaining a constant temperature and a uniform temperature distribution along the specimen at higher temperatures, each specimen was tested separately, so that temperature variations and other changing conditions occurring in the zero-stress control specimen were not reflected in the behavior of specimens of the same test series, as was true of the groups of specimens tested together in the same furnace.

The "elastic" strain as determined for the creep-test specimens in this report was defined as the total strain measured in the specimen after the load had been applied to the specimen for 20 seconds. This strain was determined by plotting the readings obtained during the first few hours of the test on logarithmic paper and reading the strain corresponding to a time of 20 seconds from the nearly straight line which resulted from this plot. The values of 20-second elastic strain are shown in the third column of tables VI and VII and in figures 23 and 24.

The total creep (including the elastic strain) was measured for all specimens at 500 hours. These data were corrected for the change in length of the specimens having zero load by subtracting the algebraic value of the change in length of this specimen. The adjusted values are shown in tables VI and VII and in figures 23 and 24.

The rate of creep did not remain constant throughout the time of testing but decreased rapidly at first and then more gradually. In order to evaluate the effect of stress on the different rates of creep, it was therefore necessary to determine the rate of creep at some definite time. The rate of creep was determined for a time of 500 hours by first correcting the data for change in length as indicated by the control specimen. The slopes of the creep-time curves at 500 hours were then measured for each of the specimens tested. The rate of creep was determined by measuring the slope of the curve represented by the test data between a time of 450 and 550 hours. The measurements were made from a logarithmic plot in which the strain scale was extended to 25 to 50 times the time scale in order to increase the accuracy of the slope measurements. The rate of creep thus obtained for each specimen is shown in tables VI and VII and plotted in figures 25 and 26.

Figure 25 shows that the rate of creep of the melamine-resin laminate was nearly the same for moderate stresses and temperatures of 77°, 130°, and 250° F, but the creep rate was much greater at 400° F. Some irregularity is shown in figure 25 for the creep-rate data, especially at 77° F. At the lower temperatures the slopes of the creep curves were so small that it was difficult to obtain an accurate determination of the rates of creep. This may account for much of the irregularity. Because of the disturbance at 200 hours shown in figure 14, the rate of creep for 40° F could not be determined.

The rate of creep for the silicone-resin material at different stresses and temperatures was reasonably consistent as shown in figure 26.

The total strain at 500 hours is also plotted in figures 23 and 24 for comparison with the 20-second elastic strain. The large increase in strain between 20 seconds and 500 hours at the highest temperature is to be noted.

The percent increase in strain at 500 hours compared with the elastic strain at 20 seconds (called the creepocity) was computed for all specimens. The values obtained are shown in tables VI and VII with average values for each laminate at each temperature.

Recovery data taken for both materials made possible a determination of the strain at 20 seconds after unloading. The 20-second recovery strains are shown in tables VI and VII. Comparison of 20-second recovery strain and 20-second elastic strain shows that the recovery strain was somewhat less than the elastic strain for all temperatures and about three-fourths the elastic strain for the silicone-resin laminate at 600° F.

Time-to-Fracture Tests

Results of time-to-fracture tests are shown plotted in figures 27 and 28. From the faired curves shown in figures 27 and 28 the stress to cause fracture in 2 and in 200 hours was determined and is listed for each material and temperature in table VIII.

All time-to-fracture tests were subject to the same conditions as the tension-creep tests. All tests followed the normal procedure except where notations to the contrary are made on the graph. Since the range of stress within which delayed fracture could be produced was rather narrow at some temperatures a considerable amount of effort was required to obtain even the few test points shown in the figures. The factors which produced the scatter of data shown have not been isolated.

ANALYSIS AND DISCUSSION OF RESULTS

Static-Tension Tests

A summary of all the mechanical properties determined for both glass-fabric laminates during this investigation is presented in table IX. The tensile properties are given by the third to seventh items.

It was observed that the melamine-resin material had a higher tensile modulus of elasticity at all comparable temperatures. For both materials the modulus of elasticity generally decreased for increased temperatures. The melamine-resin material showed a change in the slope of the stress-strain diagram at a stress of 6,000 psi or less for all four temperatures. The slope below this point was called the primary modulus of elasticity and the slope above was called the secondary modulus of elasticity. These values are given as the third and fourth items in table IX. A similar change in slope was noted for the glass-fabric laminate with an unsaturated polyester resin reported on page 15 of reference 13.

The tensile yield strength did not show a systematic variation with temperature for either glass laminate. The highest tensile yield strength for melamine resin (12,700 psi at 0.05-percent offset and 26,600 psi at 0.2-percent offset) occurred at 250° F. The tensile yield strength of silicone (10,100 psi at 0.05-percent offset) was greatest at 77° F. No tensile yield strength at 0.2-percent offset was obtained at 77° F since the stress-strain curve did not cross the 0.2-percent-offset line.

The tension modulus of elasticity of melamine resin was 25 percent lower at 400° F than at 77° F. For silicone resin the tension modulus of elasticity was 23 percent lower at 600° F than at 77° F. Considering the high and low values, the melamine-resin tensile yield strength at 0.05 was lower at 77° and 130° F than at 250° F by 15 percent. The tensile yield strength at 0.2-percent offset was 17 percent greater at 250° F than at 400° F. Silicone resin showed a tension yield strength at 0.05-percent offset 49 percent less at 600° F than at 77° F.

The tensile ultimate strength was smaller by 16 percent at 250° F than at 77° F for melamine resin. For silicone resin the tensile ultimate strength was 21 percent less at 600° F than at 77° F.

Comparison of melamine-resin and silicone-resin glass-fabric laminates with the five laminates tested in reference 11 shows that the melamine-resin material demonstrated higher tension properties by 8 percent than any of the five laminates tested previously at 77° F. However, the ultimate compressive strength of melamine resin was 43 percent smaller than the glass-fabric laminate bonded with the unsaturated polyester resin. Silicone-resin material showed lower tension and compression values than the unsaturated-polyester-resin material at 77° F.

Static-Compression Tests

The static-compression properties are summarized in table IX. The compression modulus of elasticity for the melamine-resin laminate is greater than the tension modulus at all temperatures except 400° F. The greatest difference between compression and tension moduli is 6 percent occurring at 400° F. For silicone resin the compression modulus is greater than the tension modulus by no more than 15 percent for any temperature except 600° F in which case the compression modulus is less than the tension modulus by 4 percent.

The compression yield strength of both materials decreased with increased temperature. The stress-strain curve did not cross the line at 0.2-percent offset at 77° F for either material. The compression yield strength for the highest temperature test was 60 and 66 percent less than the 77° F test for melamine resin and silicone resin, respectively. Ultimate strengths decreased with temperature increase for both materials. At the highest temperatures the ultimate strength was 47 and 74 percent less than at 77° F for melamine and silicone resin, respectively.

Ultimate strengths in compression for all temperatures and for both materials were considerably less than the corresponding ultimate strength in tension. The compression ultimate strength of melamine resin is 41 and 63 percent less than the tensile ultimate strength at 77° and 600° F, respectively.

For equal temperatures the melamine-resin glass-fabric laminate demonstrates higher tension and compression properties than the silicone-resin glass-fabric laminate. This is no doubt due in part to the comparative number of plies per unit thickness of the two laminates (62 approximately for melamine resin as compared with 45 for silicone resin).

Tension-Creep Tests

The elastic strain at 20 seconds and the total strain at 500 hours corrected for change in length due to aging at the particular test temperature appear in tables VI and VII and are shown plotted in figures 23 and 24 for all temperatures for the tension-creep tests.

The curves for the 20-second elastic strain in figures 23 and 24 may be compared with the stress-strain curves in tension, figures 10 and 11, respectively, except that the coordinates are reversed. For the melamine resin, figures 10 and 23, the 20-second-elastic-strain curves and stress-strain curves are quite similar except that the strains from the creep tests are somewhat greater. This may result from the fact that the creep specimens were at temperature 24 hours (compared with 30 minutes for the tension tests) before testing.

For the silicone resin, figures 11 and 24, the 20-second-elastic-strain curves and stress-strain curves are about the same except for the higher stresses at 425° and 600° F where the strains are much larger in the tension tests. This difference may be due to the longer time under load in the tension tests or it may be due to the longer time at temperature prior to testing in the creep tests.

Using the moduli of elasticity as a basis for comparison, the moduli of elasticity determined from the 20-second strain data for tension-creep tests are less than the moduli of elasticity of the static-tension data for all temperatures and both materials enumerated in percentages as follows: For the melamine resin at 77°, 130°, 250°, and 400° F the tension-creep moduli of elasticity are less by 15, 14, 9, and 23 percent, respectively. For the silicone resin at 77°, 250°, 425°, and 600° F the tension-creep moduli of elasticity are less by 4, 12, 9, and 12 percent. The differences in moduli of elasticity may be attributed partially to dissimilarity of the time factor.

Creepocity.- The percent increase in strain from 20 seconds to 500 hours is shown for each specimen in tables VI and VII. These data seem to verify the proposals in references 12 and 13 that the percent increase in strain, called creepocity in earlier work, is nearly independent of stress at any temperature. It was observed that the creepocity became greater for increased temperatures for both materials indicating increasingly poor resistance to creep. In spite of a large amount of scatter in the data at higher temperatures for both materials, it is evident that there is no systematic variation with stress.

As suggested in references 12 and 13 the following equation may express the creep behavior. Used with reasonable success in previous work, it is now applied to the data involving higher temperatures:

$$\epsilon = \epsilon_o\left[1 + (t/t_o)^n\right] \tag{1}$$

where

ϵ total strain, in./in.

ϵ_o time-independent strain, in./in.

t time, hr

t_o constant conveniently taken equal to unity and having dimensions of time, hr

n constant independent of stress, dimensionless

It follows from equation (1) that the creepocity Φ, which is the percent increase in strain from t_1 to t_2, may be expressed by the following equation:

$$\Phi_{12} = \frac{(t_2/t_o)^n - (t_1/t_o)^n}{1 + (t_1/t_o)^n} 100 \tag{2}$$

Exponent n.- Using the average percent increase in strain from 20 seconds to 500 hours shown in tables VI and VII the values of n were computed from equation (2) for each temperature for both laminates. Comparing this set of values of n for the melamine resin with a set previously determined (ref. 12) on the same material between 20 seconds and 1,000 hours of creep, the values of n as determined between 20 seconds and 500 hours were found to be smaller by 39 and 6 percent for 77° and 130° F, respectively. There is a good possibility that the comparatively poor agreement at 77° F may have been partially caused by the larger scatter of values of creepocity computed between 20 seconds and 1,000 hours. Of this scatter the largest value of creepocity was $2\frac{1}{2}$ times greater than the smallest. Another possibility is that equation (1) does not fit the creep data accurately enough.

Time-independent term ϵ_o.- The value of ϵ_o was determined by substituting values of n into equation (1), using values of ϵ at 20 seconds (ϵ_1) and 500 hours (ϵ_2). Comparing the average value of ϵ_o determined from ϵ_1 and ϵ_2 for melamine resin with data from reference 12 in which ϵ_o was calculated in the same manner using values of n determined from 20 seconds and 1,000 hours at 77° and 130° F, the agreement was found to be reasonable. The differences were less than 3 percent at 77° F except at 2,400 psi which rendered an ϵ_o computed from 20 seconds and 500 hours less by 7 percent than the ϵ_o computed from 20 seconds and 1,000 hours. None of the ϵ_o values at 130° F varied more than 1 percent. Similar comparisons were not made on the silicone resin since no previous computations of this nature had been performed on this material.

Calculated creep rates.- If the strain ϵ at any time is accurately defined by equation (1), then the creep rate $\dot{\epsilon}$ can be determined by differentiating equation (1) as follows:

$$\dot{\epsilon} = \frac{d\epsilon}{dt} = \frac{\epsilon_o n}{t_o} (t/t_o)^{n-1} \tag{3}$$

Creep rates at 500 hours computed from equation (3) by substituting the values of ϵ_o and n determined above are shown in tables X and XI for comparison with other creep rates at 500 hours. For the most part, the creep rates computed from equation (3) are much more consistent in stress dependence than the measured values. This is especially true of melamine resin at 77° F for which the measured values produce a scattering of data as shown in figure 25.

Effect of temperature on exponent n.- Figure 29 shows the constant n plotted against absolute temperature for both materials. The data shown in figure 29 suggest that n may be a linear function of absolute temperature and also the possibility that n has a value of zero at temperatures above zero absolute. If the straight lines shown in figure 29 are extrapolated to $n = 0$ the lines intersect the x-axis at 250° K (-10° F) for the melamine-resin laminate and 189° K (-119° F) for the silicone-resin laminate. The fact that the lines shown in figure 29 for the two laminates are nearly parallel is noteworthy.

In view of equation (1) it would seem that these materials would show no creep (that is, no time effect) at the temperatures indicated above since $n = 0$. It would be interesting to learn whether this is true. A temperature below which creep does not occur for plastics seems possible since many metals do not appear to creep at room temperature. When n is negative, equation (1) predicts that the strain will decrease with increasing time.

An anomalous behavior is indicated by equation (1) when $n = 0$ in that the strain ϵ equals $2\epsilon_o$ for any value of time other than zero (for which the strain is indeterminant).

That the strain ϵ should equal $2\epsilon_o$ does not seem too impossible since the 20-second elastic strain is approximately twice the value of ϵ_o for both laminates, especially at the lower temperatures.

Effect of temperature on time-independent term ϵ_o (first method).- The effects of temperature and stress on the coefficient ϵ_o are shown in figure 30. It was shown previously (ref. 12) that ϵ_o could be represented by a hyperbolic sine function of stress of the form

$$\epsilon_o = \epsilon_o' \sinh \sigma/\sigma_o \tag{4}$$

for the melamine-resin laminate at 40°, 77°, and 130° F. The values of ϵ_o' and σ_o for the melamine resin at 130° F have been reevaluated for the best fit to the values of ϵ_o obtained from the data at 500 hours and the values of ϵ_o' and σ_o have been determined for the data from tests of the melamine-resin laminate at 250° and 400° F. The values of ϵ_o' and σ_o are shown in tables X and XI for both materials. In figure 30 the solid lines show equation (4) using the constants of tables X and XI.

Examination of the values of ϵ_o' and σ_o shows no systematic variation with temperature. In fact it might be concluded that both values were independent of temperature and that the variation shown was scatter. However, if ϵ_o' and σ_o were independent of temperature all curves for each laminate in figure 30 would have to be coincident, which is not the case. Evidently, there is enough uncertainty or scatter in values of ϵ_o that ϵ_o' and σ_o cannot be determined accurately.

Another approach to this problem may be made as shown in the following activation-energy theory:

It has been shown previously that the creep rate $\dot{\epsilon}$ can be expressed as a function of absolute temperature T and normal stress σ as follows:

$$\dot{\epsilon} = \frac{4}{3}\frac{\lambda}{L}\frac{k}{h} Te^{\frac{\Delta S}{R}} e^{-\frac{\Delta H}{RT}} \sinh \frac{qA d\sigma}{2kT} \tag{5}$$

where

$\dot{\epsilon}$	creep rate, in./in-sec
T	absolute temperature, °K
ΔS	entropy of activation, cal/mole-°K
ΔH	energy of activation, cal/mole
σ	normal stress, dynes/sq cm
k	Boltzmann constant, 1.3805×10^{-16} ergs/°K
h	Planck constant, 6.624×10^{-27} erg-sec

R gas constant, 1.986 cal/mole-°K

λ, L, A dimensions of "unit of flow"

q stress-concentration factor

d distance through which shear stress acts in carrying unit of flow from normal to activated state

The creep rate may also be expressed as a function of stress σ and time t by combining equations (3) and (4):

$$\dot{\epsilon} = \frac{\epsilon_o' n}{t_o} (t/t_o)^{n-1} \sinh \sigma/\sigma_o \tag{6}$$

Equation (5) may be made more general by introducing the time factor from equation (6). Also it was observed above that n was nearly a linear function of absolute temperature for the two laminates tested and that the slope of the line was nearly the same for both materials. Thus this relation may be written

$$n = \alpha(T - T_a) \tag{7}$$

where α is a constant presumably independent of material and T_a is the temperature below which the material presumably shows no time sensitivity.

Substituting equation (7) in equation (6) and comparing the result with equation (5), it seems reasonable that T in equation (5) perhaps should be replaced by $(T - T_a)$ and perhaps α is proportional to $\frac{\lambda}{L} \frac{kt_o}{h}$ since k and h are fundamental physical constants and α is nearly the same for at least two materials. The factor t_o may be a relaxation time, but in any case it is needed to make n dimensionless, as required. The revised equation (5) becomes.

$$\dot{\epsilon} = \frac{4}{3t_o} e^{\frac{\Delta S}{R}} e^{-\frac{\Delta H}{RT}} \frac{\lambda}{L} \frac{kt_o}{h} (T - T_a)(t/t_o)^{\frac{\lambda}{L}\frac{kt_o}{h}(T-T_a)-1} \sinh \frac{qAd\sigma}{2kT} \tag{8}$$

Comparing equations (8) and (6) the following identities may be found:

$$\epsilon_o' = \frac{4}{3} e^{\Delta S/R} e^{-\Delta H/RT} \tag{9}$$

$$n = \frac{\lambda}{L} \frac{kt_o}{h} (T - T_a) \tag{10}$$

$$\sigma_o = \frac{2kT}{qAd} \tag{11}$$

Thus equation (8) expresses the creep rate as a function of stress, time, and temperature.

The strain ϵ may likewise be expressed as a function of stress, time, and temperature from equation (1) by substituting equation (4) for ϵ_o and substituting equations (9), (10), and (11) for ϵ_o', n, and σ_o thus:

$$\epsilon = \frac{4}{3} e^{\frac{\Delta S}{R}} e^{-\frac{\Delta H}{RT}} \left[1 + (t/t_o)^{\frac{\lambda}{L} \frac{kt_o}{h} (T - T_a)}\right] \sinh \frac{qAd\sigma}{2kT} \tag{12}$$

Effect of temperature on time-independent term ϵ_o (second method).- Substituting equations (9) and (11) into equation (4)

$$\epsilon_o = \frac{4}{3} e^{\frac{\Delta S}{R}} e^{-\frac{\Delta H}{RT}} \sinh \frac{qAd\sigma}{2kT} \tag{13}$$

For small values of σ equation (13) may be expressed approximately as follows:

$$\epsilon_o = \frac{2}{3} \frac{qAd\sigma}{kT} e^{\frac{\Delta S}{R}} e^{-\frac{\Delta H}{RT}}$$

or

$$\log_e \epsilon_o T = \log_e \frac{2}{3} \frac{qAd\sigma}{k} e^{\frac{\Delta S}{R}} - \frac{\Delta H}{R} \frac{1}{T} \tag{14}$$

Thus for a small value of stress a diagram of $\log_e \epsilon_o T$ versus $\frac{1}{T}$ should be a straight line if the temperature dependence of ϵ_o is as shown in equation (13). To test this the values of ϵ_o for a small stress were computed for each temperature from the values of ϵ_o' and σ_o given in tables X and XI. These values were used to plot the diagram shown in figure 31. The disagreement between the data points and the lines shown may be scatter of the data, or it may mean that the behavior of the material is not exactly as described by equation (13).

However, the slope of the lines is of the correct sense. Also the lines are not vertical as would have been required if ϵ_0 were independent of temperature.

The value of the activation energy ΔH was computed from the slope of those straight lines shown in figure 31. The slope of the line equals $-\frac{\Delta H}{R}$, from which ΔH was found to be about 1,460 calories per mole for both laminates instead of 4,500 calories per mole as determined previously (ref. 12) for the melamine-resin laminate using temperatures of 40°, 77°, and 130° F.

Prediction of previous computations for melamine-resin laminate.- The constants in equation (5) were evaluated from creep of the melamine-resin laminate at 40°, 77°, and 130° F and reported in a previous paper (ref. 12). It was observed, however, that the value of qAd was not constant according to the data. It is of interest to use the results of the previous analysis to predict the creep rates at 250° and 400° F for comparison with the measured values.

In making these computations $\frac{4}{3}\frac{\lambda}{L}$ was assumed to be approximately unity since λ and L are presumed to be the same order of magnitude of interatomic distance. Since qAd was not constant in the previous analysis some assumption had to be made regarding its value. Two assumptions were made: (a) It was assumed that the character of the mechanism of creep was changing in the interval 40° to 130° F which caused a change in qAd and that the change was completed at 130° F so that qAd remained constant at 29 A for higher temperatures and (b) it was assumed that qAd varied with temperature. The values of qAd were plotted as a function of temperature to logarithmic scales and the resulting straight line was extrapolated to obtain values of qAd at 250° and 400° F.

The values of the constants and qAd were inserted into equation (5) and the values of creep rate were computed. These values are listed in table X for both methods of handling qAd. The creep rates predicted from equation (5) for qAd a constant are nearest to those measured from slopes of the creep curves and those predicted from equation (5) for qAd varying with temperature were nearest to the values computed from equation (3).

Time-to-Fracture Tests

Results of time-to-fracture tests are shown for the two materials in figures 27 and 28. The results are scattered for the most part but definite trends are discernible. In general at a given temperature the time for fracture decreases with increase in stress. It was observed that the slopes decreased as the temperature was increased for both materials. At higher temperatures a small increase in load on a specimen shortened the fracture time considerably. This fact made it difficult at higher temperatures to predict a stress which would cause failure within the desired limits of time.

Figure 27 for the melamine-resin laminate shows that increasing the temperature made relatively little difference in the creep strength (i.e., the stress which produced fracture in a given time) for temperatures from 77° to 250° F. However, at 400° F a decrease in creep strength of about 12 percent was observed.

A more marked influence of temperature on the silicone-resin laminate was observed as shown in figure 28. Increasing the temperature from 77° to 250° F caused a decrease in creep strength of about 6 percent, but increasing the temperature to 425° F increased the creep strength about 26 percent. Further increase to 600° F caused a decrease of about 3 percent. No explanation of this strengthening effect of temperature has been found.

In general, at the higher temperatures for both materials, the specimens fractured within the first several seconds after loading or they endured more than 200 hours without failure. It seems possible that the creep strength may increase with time at temperature. This tendency may have been the factor which made it difficult to obtain fracture data between 0.001 hour and 100 hours.

This effect of age strengthening at 400° F for the melamine-resin material was apparent from the results of step creep tests. The weakening effect mentioned just previously and apparent from the 400° F curve in figure 27 applied only to those specimens stressed between 29,000 and 30,000 psi during the first few hours of loading. Six specimens loaded at various stresses between 30,000 and 33,000 psi failed instantaneously. Yet one preliminary step test at 400° F performed on the melamine-resin material was stressed initially at 20,000 psi and after the stresses were stepped up by 2,000-psi intervals over a period of 440 hours the material finally failed at a stress of 38,000 psi. Two other step tests at 400° F were performed between the limits of 28,000 to 36,000 psi with fracture in 454 hours and 29,000 to 34,000 psi with fracture in 430 hours. These results suggest that the material increases in strength with time at this temperature. On the other hand, a "coaxing effect" resulting from starting the stressing below the creep strength and gradually increasing the stress may have produced the strengthening. No results of a similar nature were shown so distinctly by the silicone-resin step creep tests.

Silicone-resin specimens of two different types were tested at 77° F. The slight difference in fracture time indicated for the two types of specimens may be the result of one or both of two effects. First, some effect may have resulted from differences in conditioning time in the laboratory between the machining date and testing date. Second, aging which was noticed at higher temperatures may have been a factor. Specimens of the type shown in figure 1(d) were conditioned in the laboratory for approximately 2 months before testing. Specimens of the type shown in figure 1(c) were exposed to the same conditions 11 to 18 months before testing.

One specimen of each type tested at the same stress of 10,500 psi failed at the center of its gage length in almost the same time interval. This seems to discount the effect of aging at 77° F. The other three specimens of the type shown in figure 1(d) failed at the grip which suggests that they may have failed prematurely.

SUMMARY OF RESULTS

The following results were obtained from tests of the effect of temperatures up to 400° and 600° F on creep, stress-rupture, and static properties of melamine-resin and silicone-resin glass-fabric laminates:

1. Both glass-fabric laminates showed a decrease in static-tensile and static-compressive properties with increasing temperature. At lower temperatures the melamine-resin glass-fabric laminate showed more desirable mechanical properties than the silicone-resin glass-fabric laminate. The melamine-resin material is not suited for the high-temperature conditions in which silicone resin will respond favorably. The silicone-resin material did not decompose readily at 600° F.

2. The melamine-resin material demonstrated a pronounced weakening in resistance to fracture for the first few hours of exposure to the 400° F temperature. Gradually the material seemed to strengthen and at approximately 430 hours was able to withstand stresses ranging from 34,000 to 38,000 psi.

3. The silicone-resin material did not exhibit the initial weakening effect at high temperatures for the first few hours after loading. Instead an immediate strengthening effect was noticeable and the material showed indirect signs of continuing to strengthen with time.

4. The creep-test data indicate that the rate of creep increases with higher temperatures for both materials. The creep test results at various temperatures seem to support the proposition that the percent increase in strain due to creep for a given time interval (creepocity) is independent of stress. This being true, creepocity may be useful in comparing the creep resistance of materials.

5. Computations made from the creepocity values indicate that the time exponent n is a linear function of absolute temperature and that there may be no time effect at certain predicted low temperatures on these two materials. No tests were performed at these low temperatures, however.

6. Some evidence is offered to support the activation-energy theory. The activation energy was found to be about 1,460 calories per mole for both laminates. An equation is presented which describes the creep as a function of stress, time and temperature.

7. Results of recovery data indicate that, in general, higher temperatures cause a decrease in recovery strain for both materials.

University of Illinois,
Urbana, Ill., October 27, 1953.

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TABLE I.- PREPARATION AND COMPOSITION OF LAMINATES

	Type of laminate	
	Melamine-resin glass-fabric	Silicone-resin glass-fabric
Designation of laminate . . .	Textolite No. 11508 Br.	Grade GSS
Laminator	General Electric Co.	Taylor Fibre Co.
Resin		
Manufacturer	American Cyanamid Co.	Dow Corning Corp.
Number	Melmac 402	DC-2103
Type	Melamine formaldehyde	Silicone
Process	. . . .	Single stage
Reaction rate	. . . .	Slow
Composition of resin . . .	1 mole melamine, 2 moles formaldehyde	
Catalyst used	None	Triethanolamine, 0.15 percent
Solvent	95 percent water, 5 percent butanol	Toluene
Solids, percent	60	60
pH	8.4	----------------------------
Fabric		
Kind	ECC-11-128	Owens-Corning staple-fiber glass-cloth ESS-261, washed to sizing content of 0 0.5 percent
Yarn		
Warp	$225\frac{1}{3}$: 5 turns per inch (Z) in twisting 4.4 turns per inch (S) in plying	Glass fiber ESE 40/2
Woof	Same as warp	Same as warp
Weave	Plain	Plain
Thickness, in.	0.007	0.015
Weight raw, oz/sq yd . . .	6.00	10.7
Threads/in.	42 by 32	20 by 14
Tensile strength		
Warp, lb/in. minimum . .	250	170
Woof, lb/in. minimum . .	200	120
Molding conditions		
Preparation		
Number of plies	62 (estimate)	45
Percent resin by weight in -		
Body of laminate . . .	. . . .	45
Surface layer	. . . .	45
Lay of lamination	Parallel laminated	Unidirectional
Molding		
Machine used	. . . .	Press
Heating		
Type	. . . .	Electric platens
Uniformity, °F	. . . .	±5
Temperature, °F	284	485
Molding pressure, psi . .	1,250	1,800
Time of heating cycle, hr	1	$3\frac{1}{2}$ (3 hr at 485° F)
Time of cooling cycle, hr	. . . .	2 (steam and water)
Temperature at which removed from pressure, °F	Room temperature	50

TABLE II.- TENSION TESTS OF MELAMINE-RESIN GLASS-FABRIC LAMINATES

Temperature, °F	Specimen	Modulus of elasticity, psi		Yield strength, psi		Ultimate strength, psi	Rate of strain, in./in-min
		Primary	Secondary	0.05-percent offset	0.2-percent offset		
77	[a]B1	3.99×10^6	2.96×10^6	10,000	25,300	43,500	0.0011
	B2	3.78	2.96	11,900	27,900	44,100	.0014
	B3	3.71	2.92	11,700	28,300	43,200	.0018
	B4	3.96	2.92	9,800	25,400	40,100	.0016
	B5	3.92	2.96	10,100	25,500	45,600	.0015
	B6	3.87	2.93	10,300	25,300	43,500	.0016
		[b]3.85	[b]2.94	[b]10,800	[b]26,500	[b]43,200	[b].0016
130	[a]B8	4.32	3.15	10,300	23,300	34,700	0.0028
	[c]B9	3.72	3.15	15,000	31,400	36,900	.0013
	B10	3.58	2.88	11,300	26,600	42,000	.0015
	B11	3.74	2.87	9,800	25,000	37,300	.0016
	B12	3.78	3.07	11,300	26,400	38,900	.0018
		[b]3.70	[b]2.94	[b]10,800	[b]26,000	[b]39,400	[b].0016
250	[a]B13	2.97	2.48	12,600	25,500	39,370	0.0020
	B14	3.00	2.47	13,100	27,200	33,600	.0015
	B15	3.03	2.54	13,500	27,600	37,800	.0017
	B16	3.16	2.62	12,300	25,500	33,300	.0016
	B17	3.06	2.60	12,000	26,100	39,200	.0016
		[b]3.06	[b]2.56	[b]12,700	[b]26,600	[b]36,000	[b].0016
400	[d]B19	3.82	2.83	8,500	17,300	40,300	0.0014
	B20	2.80	2.50	13,800	25,100	38,300	.0016
	B21	3.08	2.65	9,500	19,000	34,700	.0019
	B22	3.02	2.60	10,600	20,000	36,200	.0018
	B23	3.00	2.74	11,300	23,800	37,100	.0018
		[b]2.97	[b]2.62	[b]11,300	[b]22,000	[b]36,600	[b].0018

[a]Excluded from average because strain rate was outside limits of 0.0016 ± 0.0003 in./in-min.

[b]Average value.

[c]Excluded from average because furnace was removed for 30 min. during test so that grips could be tightened.

[d]Excluded from average because specimen slipped in grips during test.

TABLE III.- TENSION TESTS OF SILICONE-RESIN GLASS-FABRIC LAMINATE

Temperature, °F	Specimen	Primary modulus of elasticity, psi	Yield strength, psi		Ultimate strength, psi	Rate of strain, in./in-min
			0.05-percent offset	0.2-percent offset		
77	B1	2.05×10^6	10,100	(a)	16,000	0.0014
	B2	2.10	8,400	(a)	17,700	.0015
	B3	2.05	10,500	(a)	16,700	.0017
	B4	1.94	10,000	(a)	15,900	.0017
	B5	2.00	10,500	(a)	15,900	.0017
	B6	1.94	10,900	(a)	16,000	.0018
		[b]2.01	[b]10,100	(a)	[b]16,400	[b].0016
250	B19	1.90	5,900	12,200	15,200	0.0017
	B20	1.90	5,100	11,200	14,800	.0015
	B21	1.90	6,100	12,400	15,200	.0015
	B22	1.90	5,800	12,300	13,600	.0017
		[b]1.90	[b]5,700	[b]12,000	[b]14,700	[b].0016
425	[c]B14	1.51	6,900	8,600	14,400	0.0020
	B15	1.54	6,700	8,630	13,500	.0019
	B16	1.70	5,400	7,530	13,200	.0018
	B17	1.50	6,500	8,750	14,600	.0017
		[b]1.58	[b]6,200	[b]8,300	[b]13,700	[b].0018
600	B8	1.61	5,300	6,900	13,400	0.0018
	B9	1.55	5,000	6,300	13,600	.0018
	B10	1.54	5,100	6,700	11,700	.0017
		[b]1.57	[b]5,100	[b]6,600	[b]12,900	[b].0018

[a]Stress-strain curve did not cross 0.2-percent-offset line before fracture.

[b]Average value.

[c]Strain rate was outside limits of 0.0016 ± 0.0003 in./in-min. Therefore, data were excluded from average.

TABLE IV.- COMPRESSION TESTS OF MELAMINE-RESIN GLASS-FABRIC LAMINATE

Temperature, °F	Specimen	Modulus of elasticity, psi	Yield strength, psi		Ultimate strength, psi	Rate of strain, in./in-min
			0.05-percent offset	0.2-percent offset		
77	A1	4.00×10^6	24,500	(a)	25,900	0.0014
	A2	3.88	------	(a)	25,900	.0017
	A3	4.06	22,200	(a)	25,800	.0016
	A4	3.94	24,700	(a)	26,100	.0016
	A5	3.98	------	(a)	26,100	.0016
	A6	3.98	------	(a)	24,700	.0016
		[b]3.97	[b]23,800	(a)	[b]25,700	[b].0016
130	A13	3.90	17,200	20,900	21,100	0.0019
	A14	3.80	18,600	(a)	21,100	.0015
	A15	3.92	17,700	(a)	20,600	.0016
	A16	3.70	18,400	(a)	20,800	.0017
		[b]3.83	[b]18,000		[b]20,900	[b].0017
250	A19	3.18	11,800	15,000	16,200	0.0017
	A20	3.12	12,200	15,000	16,300	.0017
	A21	3.03	10,700	14,300	16,100	.0018
		[b]3.11	[b]11,500	[b]14,800	[b]16,200	[b].0017
400	[c]A25	2.60	10,200	12,200	13,500	0.0024
	A27	2.83	9,300	12,200	13,800	.0016
	A28	2.76	9,700	12,100	13,300	.0018
	A29	2.60	9,700	12,000	13,700	.0018
		[b]2.73	[b]9,600	[b]12,100	[b]13,600	[b].0017

[a]Stress-strain curve did not cross 0.2-percent-offset line before fracture.

[b]Average value.

[c]Rate of strain was outside limits of 0.0016 ± 0.0003 in./in-min. Therefore, data were excluded from average.

TABLE V.- COMPRESSION TESTS OF SILICONE-RESIN GLASS-FABRIC LAMINATE

Temperature, °F	Specimen	Modulus of elasticity, psi	Yield strength, psi		Ultimate strength, psi	Rate of strain, in./in-min
			0.05-percent offset	0.2-percent offset		
77	[a]A2	2.25×10^6	8,800	(b)	11,500	0.0010
	A1	2.35	8,200	(b)	12,300	.0019
	A3	2.70	5,200	10,700	10,800	.0017
	A4	2.15	9,000	(b)	11,100	.0014
	A5	2.33	7,900	(b)	11,000	.0013
		[c]2.38	[c]7,000		[c]11,300	[c].0016
250	[a]A25	2.25	4,500	6,200	6,400	0.0020
	A23	1.98	4,700	5,700	5,700	.0015
	A24	2.11	4,500	6,000	6,100	.0015
		[c]2.05	[c]4,600	[c]5,800	[c]5,900	[c].0015
425	A27	1.36	3,200	3,700	3,700	0.0014
	A28	1.96	3,000	3,700	3,700	.0013
	A29	1.82	3,000	3,700	3,800	.0015
		[c]1.71	[c]3,100	[c]3,700	[c]3,700	[c].0014
600	[a]A17	1.72	2,800	3,000	3,000	0.0012
	[a]A18	2.04	2,600	3,100	3,100	.0008
	A19	1.48	2,700	3,100	3,100	.0014
	A21	1.50	2,600	3,000	3,000	.0018
		[c]1.49	[c]2,700	[c]3,000	[c]3,100	[c].0016

[a]Rate of strain was outside limits of 0.0016 ± 0.0003 in./in-min. Therefore, data were excluded from average.

[b]Stress-strain curve did not cross 0.2-percent-offset line before fracture.

[c]Average value.

TABLE VI.- TENSION CREEP TESTS OF MELAMINE-RESIN GLASS-FABRIC LAMINATE

Temperature, °F	Stress, psi	20-sec elastic strain, percent	Total creep at 500 hr, percent (a)	Rate of creep at 500 hr, in./in-hr (a)	Increase in strain, 20 sec to 500 hr, percent	Total strain at 1,000 hr, in./in-hr (a)	Increase in strain, 20 sec to 1,000 hr, percent	20-sec recovery strain at time noted, percent
								3,500 hr
40	4,100	0.1186	(b)	(b)	(b)	0.1310	10.4	0.2522
	8,200	.2577				.2787	8.2	.3858
	12,000	.3944				.4299	7.7	.5453
	16,400	.5508				.5983	8.6	
							[c]8.7	
								3,800 hr
77	2,400	0.0660	0.0700	1.45×10^{-7}	6.06	0.0805	22.0	0.0649
	4,800	.1449	.1570	1.95	8.35	.1681	16.0	.1405
	7,200	.2289	.2447	1.78	6.90	.2554	11.6	.2202
	9,600	.3114	.3308	1.38	6.23	.3402	9.3	.3013
	12,000	.4004	.4256	1.62	6.29	.4342	8.5	.3837
	14,400	.4842	.5148	2.26	6.32	.5260	8.6	.4724
	16,800	.5700	.6082	2.52	6.70	.6212	9.0	.5532
					[c]6.69		[c]12.1	
								3,300 hr
130	4,100	0.1285	0.1319	0.79	18.2	0.1554	20.9	0.1245
	8,200	.2782	.3204	1.58	15.2	.3288	18.2	.2683
	12,000	.4225	.4882	2.70	15.6	.4985	18.0	.4080
					[c]16.3		[c]19.0	
								600 hr
250	7,500	0.267	0.369	[d]2.1	38.2	(e)	(e)	0.2596
	15,000	.605	.790	[d]6.8	30.6	(e)	(e)	.5605
	22,500	.970	(e)	(e)	(e)	(e)	(e)	(e)
	30,000	1.351	1.835	[d]16.8	35.7	(e)	(e)	1.271
					[c]34.8			
								500 hr
400	10,000	0.450	0.734	43	63.2	(e)	(e)	0.4131
	20,000	.994	(e)	(e)	(e)	(e)	(e)	(e)
	26,400	1.498	2.406	53	60.6	(e)	(e)	1.294
	28,000	[f]1.916	2.672	58	(f)	(e)	(e)	(e)
	29,000	1.871	(e)	(e)	(e)	(e)	(e)	(e)
	29,350	1.842	2.820	54	52.1	(e)	(e)	(e)
					[c]59.0			

[a]Values corrected for change in length of control specimen.

[b]Disturbance at about 500 hr.

[c]Average value.

[d]Creep rate was determined between 350 and 450 hr because of a disturbance near 500 hr.

[e]Test was concluded before the time indicated.

[f]Extensometer did not function properly.

TABLE VII.- TENSION CREEP TESTS OF SILICONE-RESIN GLASS-FABRIC LAMINATE

Temperature, °F	Stress, psi	20-sec elastic strain, percent	Total creep at 500 hr, percent (a)	Rate of creep at 500 hr, in./in-hr (a)	Increase in strain, 20 sec to 500 hr, percent	20-sec recovery strain at time noted, percent
						14,000 hr
77	1,100	0.0546	0.0605	0.6×10^{7}	11.8	0.0525
	2,200	.1083	.1254	1.0	15.8	.1062
	3,300	.1690	.1971	1.4	16.8	.1655
	4,400	.2174	.2568	1.7	18.2	.2136
	5,500	.2874	.3419	2.3	18.9	.2801
	6,600	.3651	.4334	2.5	18.6	.3533
	7,700	.4257	.5293	3.0	23.8	.4175
					[b]17.7	
						600 hr
250	2,000	0.1180	0.1851	2.0	56.9	0.1032
	4,000	.2513	.3265	3.9	30.7	.2297
	6,000	.3980	.5296	4.9	33.1	.3604
	8,000	.5108	.7186	6.9	44.9	.5064
					[b]41.4	
						500 hr
425	4,000	0.275	0.411	4.6	49.6	0.2416
	[c]8,000	.700	1.039	12.0	48.2	.5022
	10,000	1.257	1.566	14.0	24.6	.7639
	11,500	1.361	(e)	(e)	(e)	(e)
					[b]40.8	
						500 to 650 hr
600	4,000	(d)	(d)	13.5	(d)	(d)
	6,000	0.448	0.947	30.5	111.8	0.3620
	8,000	0.715	(e)	(e)	(e)	(e)
	10,000	.970	1.746	49.5	80.0	.7379
	10,500	.971	1.693	48.5	74.5	.6868
	11,000	1.140	1.915	48.0	68.0	
					[b]83.6	

[a]Values corrected for change in length of control specimen.

[b]Average value.

[c]Temperature was 525° F for about 1 hr prior to loading.

[d]Initial reading was in error.

[e]Load changed before 500 hr.

TABLE VIII.- TIME-TO-FRACTURE CREEP TESTS

Glass-fabric laminate	Temperature, °F	Creep strength, psi, for fracture in -	
		2 hr	200 hr
Melamine resin	77	36,300	33,300
	130	34,800	32,800
	250	34,400	33,200
	400	29,400	29,200
Silicone resin	77	10,800	9,700
	250	10,000	9,300
	425	11,600	11,500
	600	11,900	11,800

TABLE IX.- SUMMARY OF MECHANICAL PROPERTIES DETERMINED FOR GLASS-FABRIC LAMINATES

Property	Melamine resin at a temperature, °F, of -					Silicone resin at a temperature, °F, of -			
	40	77	130	250	400	77	250	425	600
Molding pressure, psi	-------	1,250	-------	-------	-------	1,800	-------	-------	-------
Specific gravity	-------	1.90	-------	-------	-------	1.68	-------	-------	-------
Tension modulus, primary, psi	-------	3.85×10^6	3.70×10^6	3.06×10^6	2.97×10^6	2.01×10^6	1.90×10^6	1.58×10^6	1.57×10^6
Tension modulus, secondary, psi	-------	2.94×10^6	2.94×10^6	2.56×10^6	2.62×10^6	-------	-------	-------	-------
Tension yield strength at 0.05-percent offset, psi	-------	10,800	10,800	12,700	11,300	10,100	5,700	6,200	5,100
Tension yield strength at 0.2-percent offset, psi	-------	26,500	26,000	26,600	22,000	(a)	12,000	8,300	6,600
Ultimate strength in tension, psi	-------	43,200	39,400	36,000	36,600	16,400	14,700	13,700	12,900
Compression modulus, psi	-------	3.97×10^6	3.83×10^6	3.11×10^6	2.73×10^6	2.38×10^6	2.05×10^6	1.71×10^6	1.49×10^6
Compression yield strength at 0.05-percent offset, psi	-------	23,800	18,000	11,500	9,600	7,600	4,600	3,100	2,700
Compression yield stress at 0.2-percent offset, psi	-------	(a)	(a)	14,800	12,100	(a)	5,800	3,700	3,000
Ultimate strength in compression, psi	-------	25,700	20,900	16,200	13,600	11,300	5,900	3,700	3,100
Total creep at 500 hr, percent	-------	[b]0.4256	[b]0.4882	[b]0.60	[b]0.92	[c]0.385	[c]0.5296	[c]0.670	[c]0.947
Average for creep tests at several stresses of increase in strain from 20 sec to 500 hr, percent	-------	6.69	16.3	34.8	59.0	17.7	41.4	40.8	83.6
Rate of creep at 500 hr, in./in-hr	-------	[b]1.62×10^{-7}	[b]2.70×10^{-7}	[b]5.0×10^{-7}	[b]44.0×10^{-7}	[c]2.3×10^{-7}	[c]4.9×10^{-7}	[c]8.8×10^{-7}	[c]30.5×10^{-7}
20-sec. elastic strain, percent	[b]0.3944	[b]0.4004	[b]0.4225	[b]0.47	[b]0.55	[c]0.315	[c]0.3980	[c]0.445	[c]0.448
20-sec. recovery strain, percent	[b]0.3858	[b]0.3837	[b]0.4080	[b]0.43	[b]0.495	[c]0.31	[c]0.3604	[c]0.365	[c]0.3620
Creep strength at 200 hr, psi	-------	33,300	32,800	33,200	29,200	9,700	9,300	11,500	11,800

[a]Stress-strain curve did not cross 0.2-percent-offset line before fracture.

[b]12,000-psi stress.

[c]6,000-psi stress.

TABLE X.- SUMMARY OF COMPUTED CREEP DATA FOR MELAMINE-RESIN GLASS-FABRIC LAMINATE

Temperature, °F	Stress, psi	ϵ_0, average of values from 20-sec and 500-hr computations, percent	Rate of creep at 500 hr, in./in-hr: Measured (a)	Rate of creep at 500 hr, in./in-hr: Computed from eq. (3) using n_1	Rate of creep at 500 hr, in./in-hr: Computed from eq. (5), qAd = Constant	Rate of creep at 500 hr, in./in-hr: Computed from eq. (5), qAd varying with temperature	Time exponent n: From 20-sec and 500-hr data, n_1	Time exponent n: From 20-sec and 1,000-hr data, n_2	ϵ_0', percent	σ_0, psi
40	4,100	[b]0.0618	------------	[c]0.184×10^{-7}	------------	------------	------------	0.0137	0.424	26,000
	8,200	[b].1323	------------	[c].395	------------	------------				
	12,000	[b].2035	------------	[c].608	------------	------------				
	16,400	[b].2853	------------	[c].851	------------	------------				
77	2,400	0.0339	1.45×10^{-7}	0.82	------------	------------	0.0113	0.0186	0.575	35,000
	4,800	.0753	1.95	1.81	------------	------------				
	7,200	.1182	1.78	2.84	------------	------------				
	9,600	.1600	1.38	3.86	------------	------------				
	12,000	.2061	1.62	4.97	------------	------------				
	14,400	.2490	2.26	6.00	------------	------------				
	16,800	.2938	2.52	7.20	------------	------------				
130	4,100	0.0692	0.79	0.43	------------	------------	0.0263	0.0281	0.255	15,000
	8,200	.1479	1.58	0.92	------------	------------				
	12,000	.2249	2.70	1.39	------------	------------				
250	7,500	0.153	[d]2.1	2.19	3.37×10^{-7}	2.08×10^{-7}	0.0516		0.574	27,000
	15,000	.338	[d]6.8	4.84	6.8	4.21				
	30,000	.771	[d]16.8	11.01	14.1	8.54				
400	10,000	0.274	43	7.16	22.1	6.5	0.0797		0.569	21,000
	26,400	.906	53	23.7	58.5	17.4				
	29,350	1.089	54	28.5	66.5	19.4				
									[e]0.479	[e]24,800

[a]Values corrected for change in length of control specimen.

[b]Computed from 20-sec and 1,000-hr computations.

[c]Computed values from ref. 4 based on values of n_2 and ϵ_0 determined from 20-sec and 1,000-hr computations.

[d]Creep rate was determined between 350 and 450 hr because of a disturbance near 500 hr.

[e]Average value.

TABLE XI.- SUMMARY OF COMPUTED CREEP DATA FOR SILICONE-RESIN GLASS-FABRIC LAMINATE

Temperature, °F	Stress, psi	ϵ_o, average of values from 20-sec and 500-hr computations, percent	Rate of creep at 500 hr, in./in-hr		Time exponent n from 20-sec and 500-hr data	ϵ_o', percent	σ_o, psi
			Measured	Computed from eq. (3)			
77	1,100	0.0284	0.6×10^{-7}	0.19×10^{-7}	0.0283	0.203	7,800
	2,200	.0579	1.0	.39			
	3,300	.0906	1.4	.62			
	4,400	.1169	1.7	.80			
	5,500	.1555	2.3	1.06			
	6,600	.1960	2.5	1.34			
	7,700	.2340	3.0	1.60			
250	2,000	0.0719	2.0	1.26	0.0600	0.278	8,200
	4,000	.1396	3.9	2.44			
	6,000	.2230	4.9	3.9			
	8,000	.2960	6.9	4.9			
425	4,000	0.163	4.6	2.79	0.0591	0.304	7,360
	8,000	.413	12.0	7.07			
	10,000	.681	14.0	11.63			
600	6,000	0.305	30.5	12.1	0.1040	0.392	8,200
	10,000	.606	49.5	24.2			
	10,500	.596	48.5	23.8			
	11,000	.689	48.0	27.5			
						[a]0.294	[a]7,900

[a]Average values.

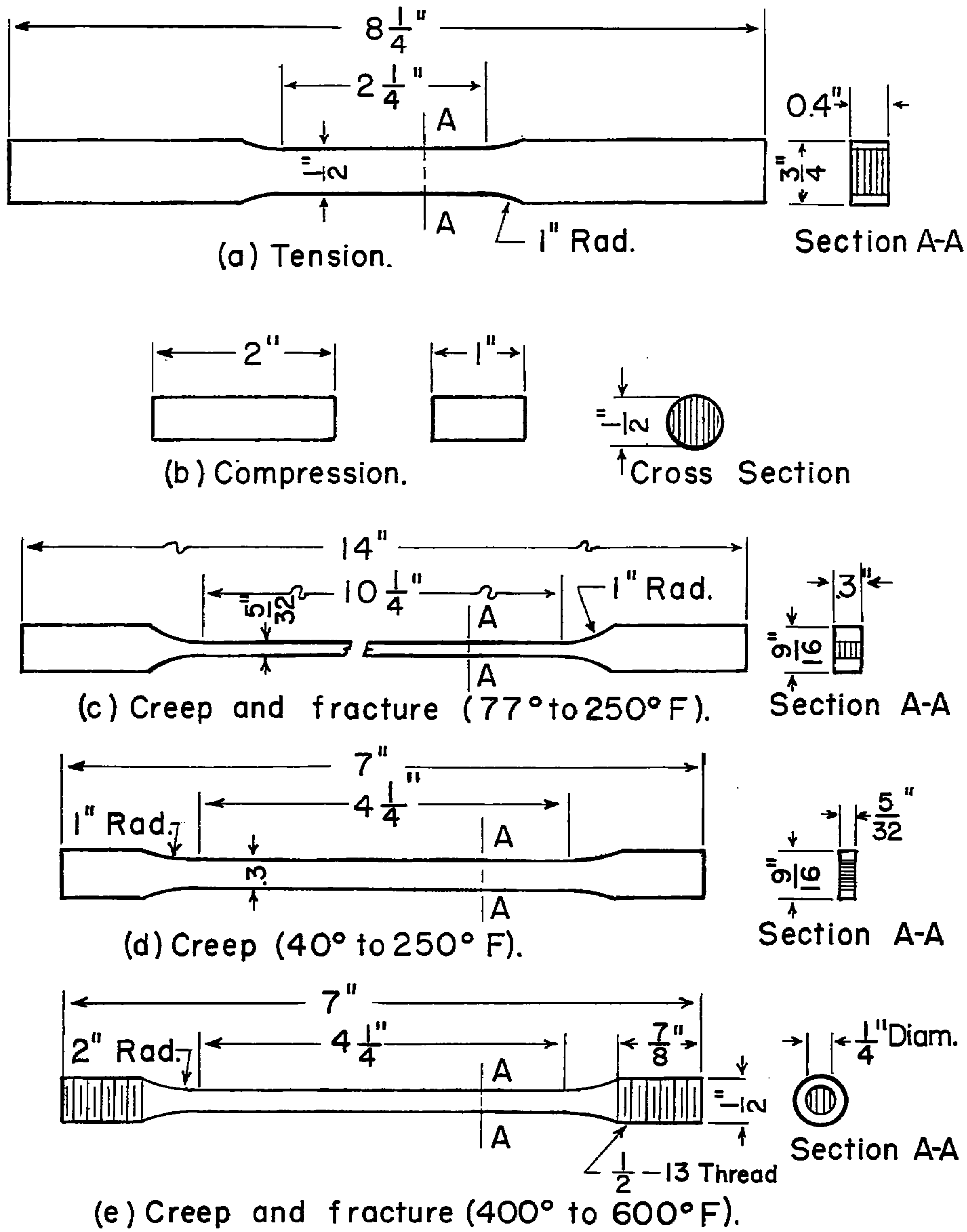

Figure 1.- Static and creep specimens. Cross-hatched lines indicate planes of laminations.

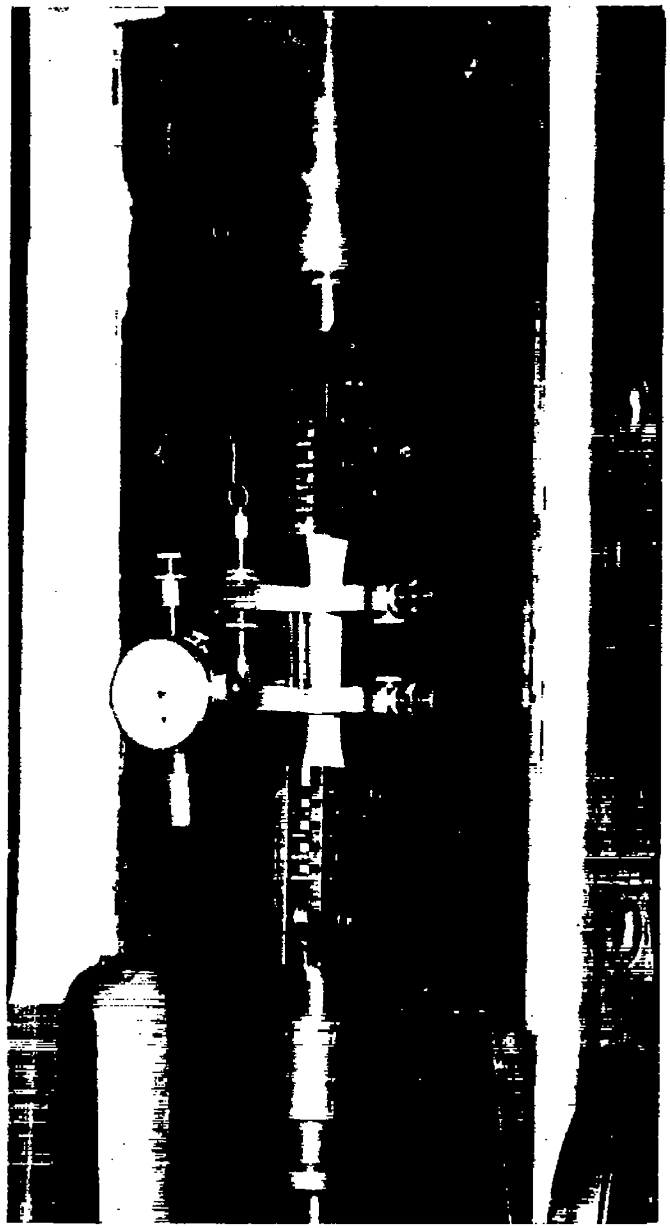

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Figure 2.- Apparatus used for static-tension tests.

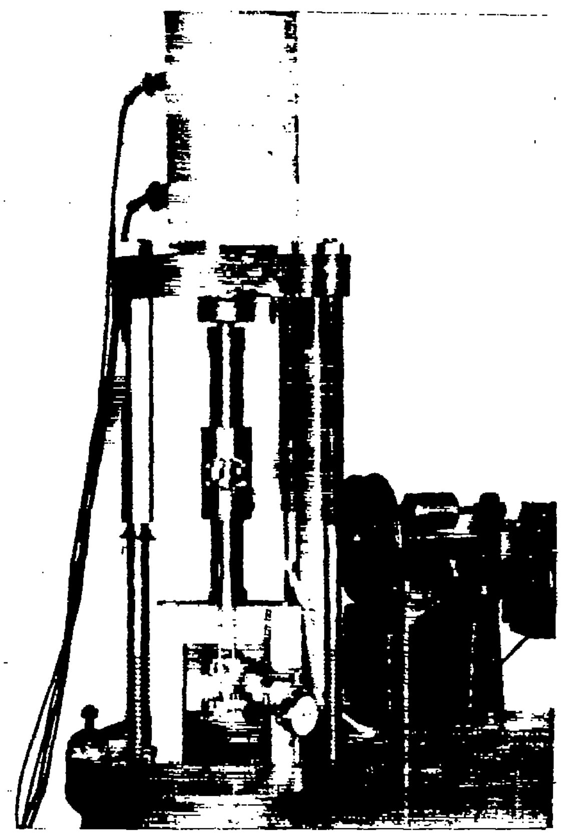

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Figure 3.- Apparatus used for static-compression tests.

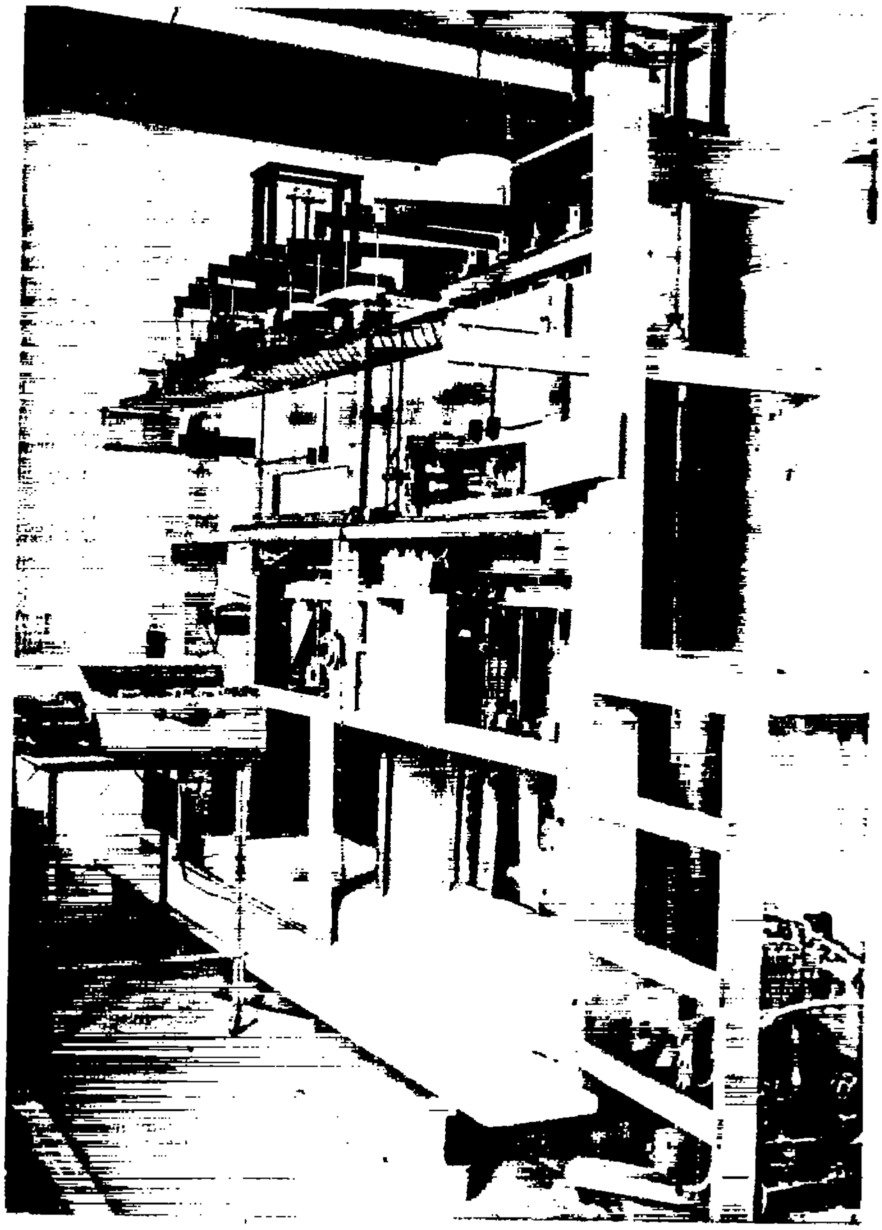

Figure 4.- Multiple-creep machine used for tests at 40°, 130°, and 250° F.

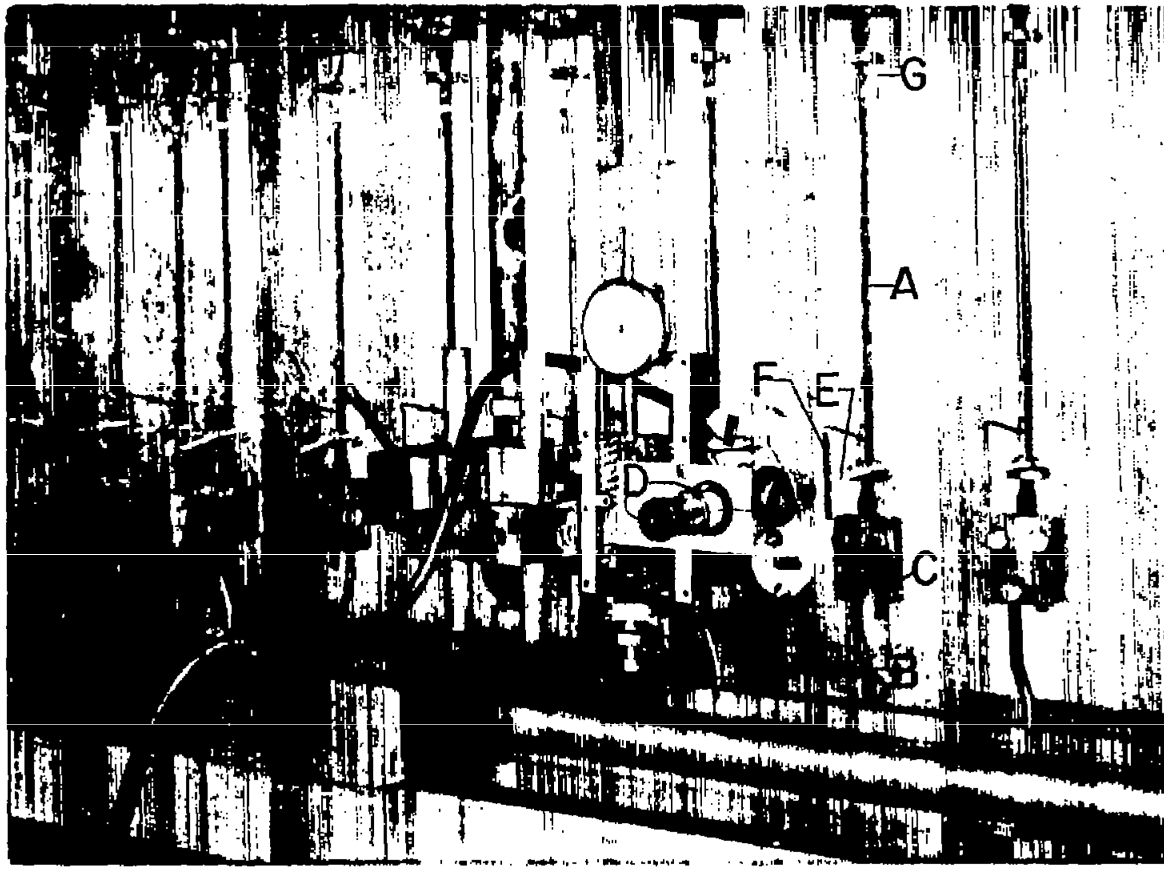

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Figure 5.- Creep-measuring apparatus used with multiple-creep machine.

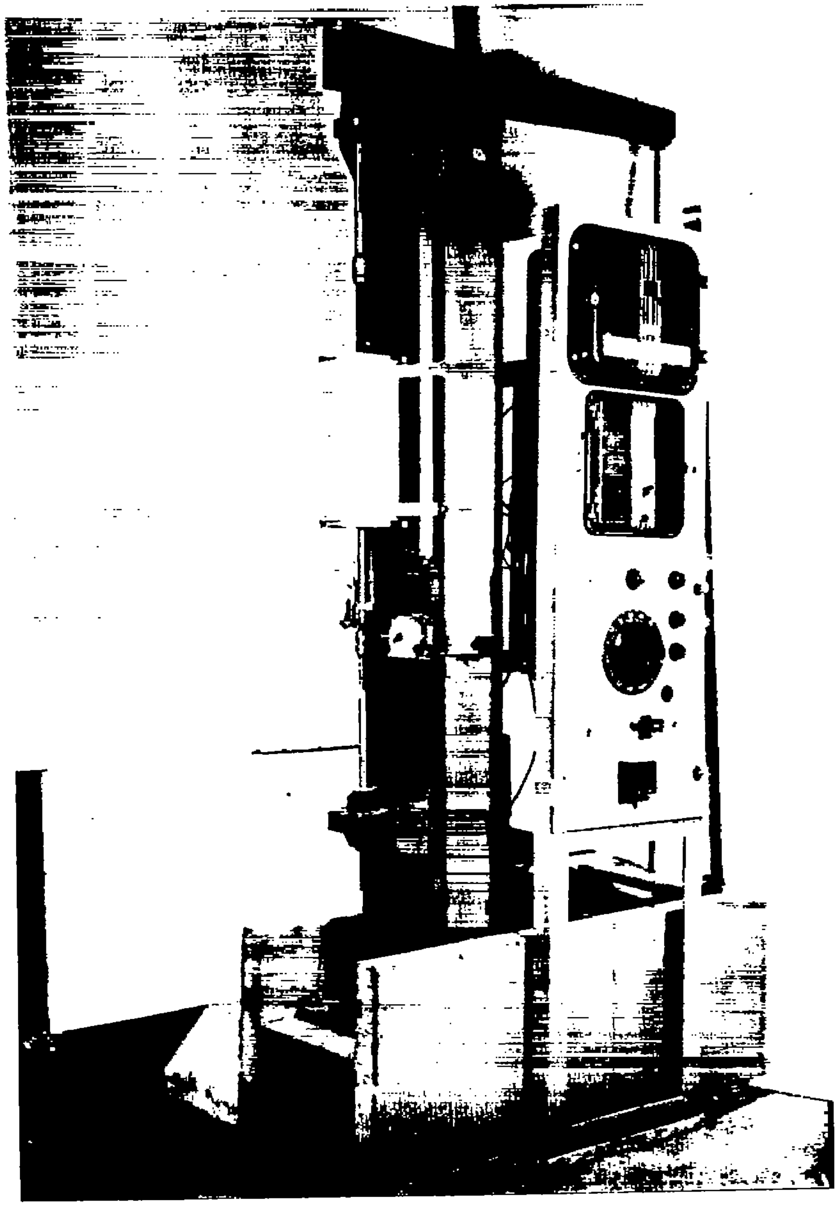

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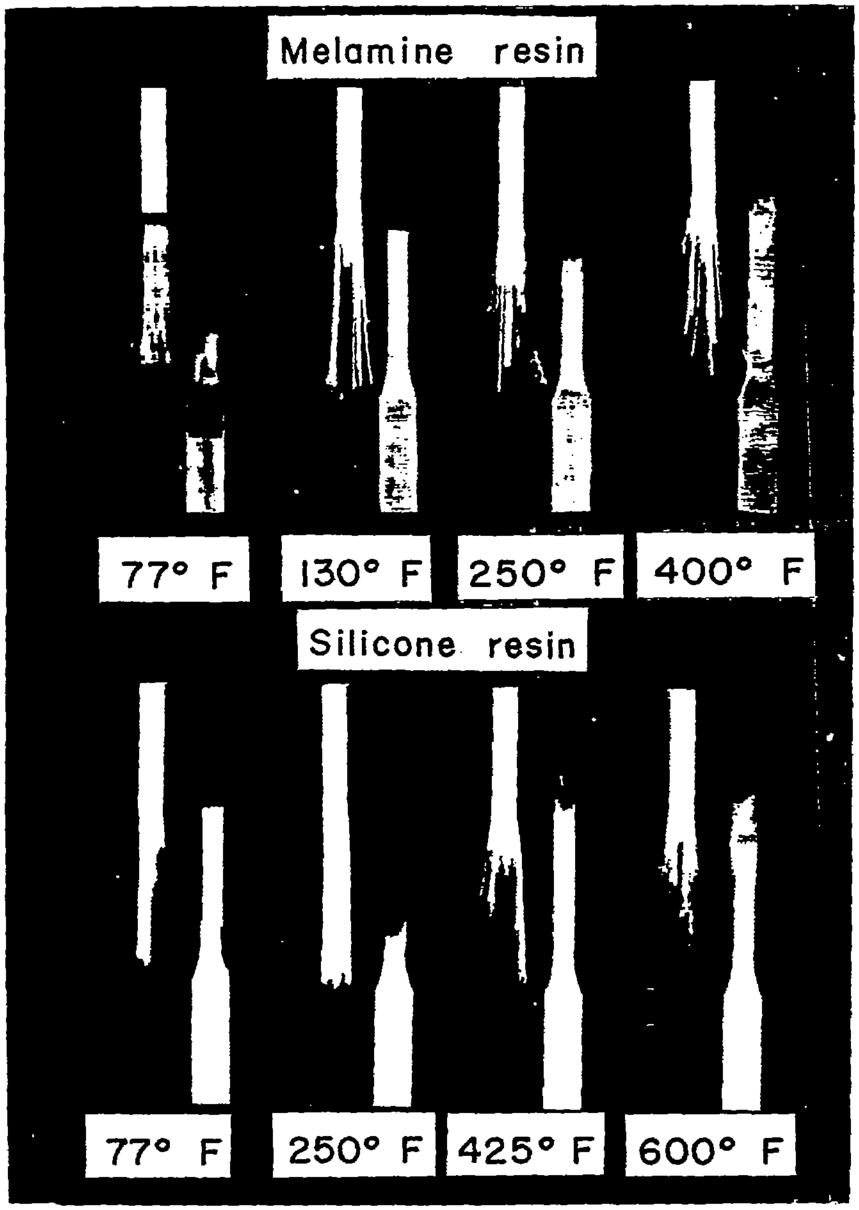
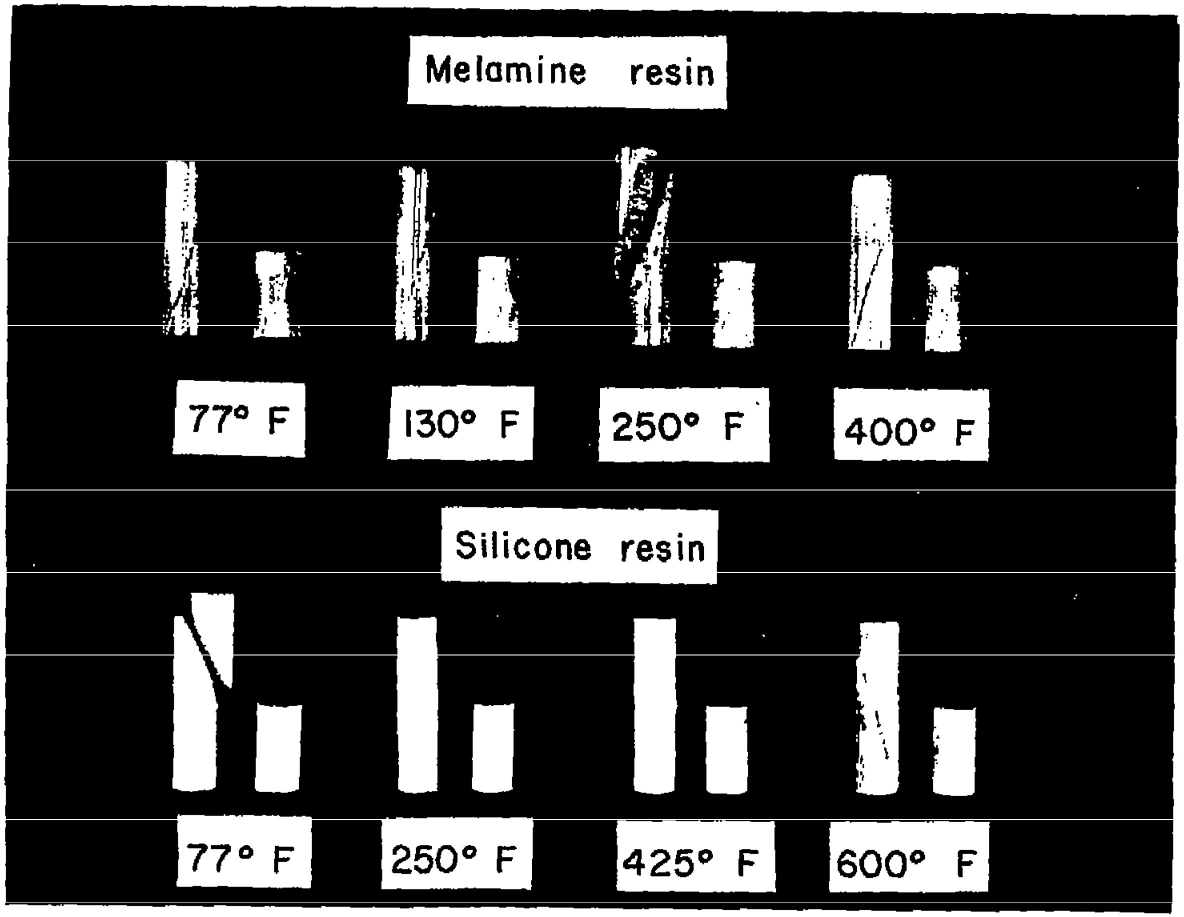
Figure 6.- Creep machine used for tests at 400° to 600° F.



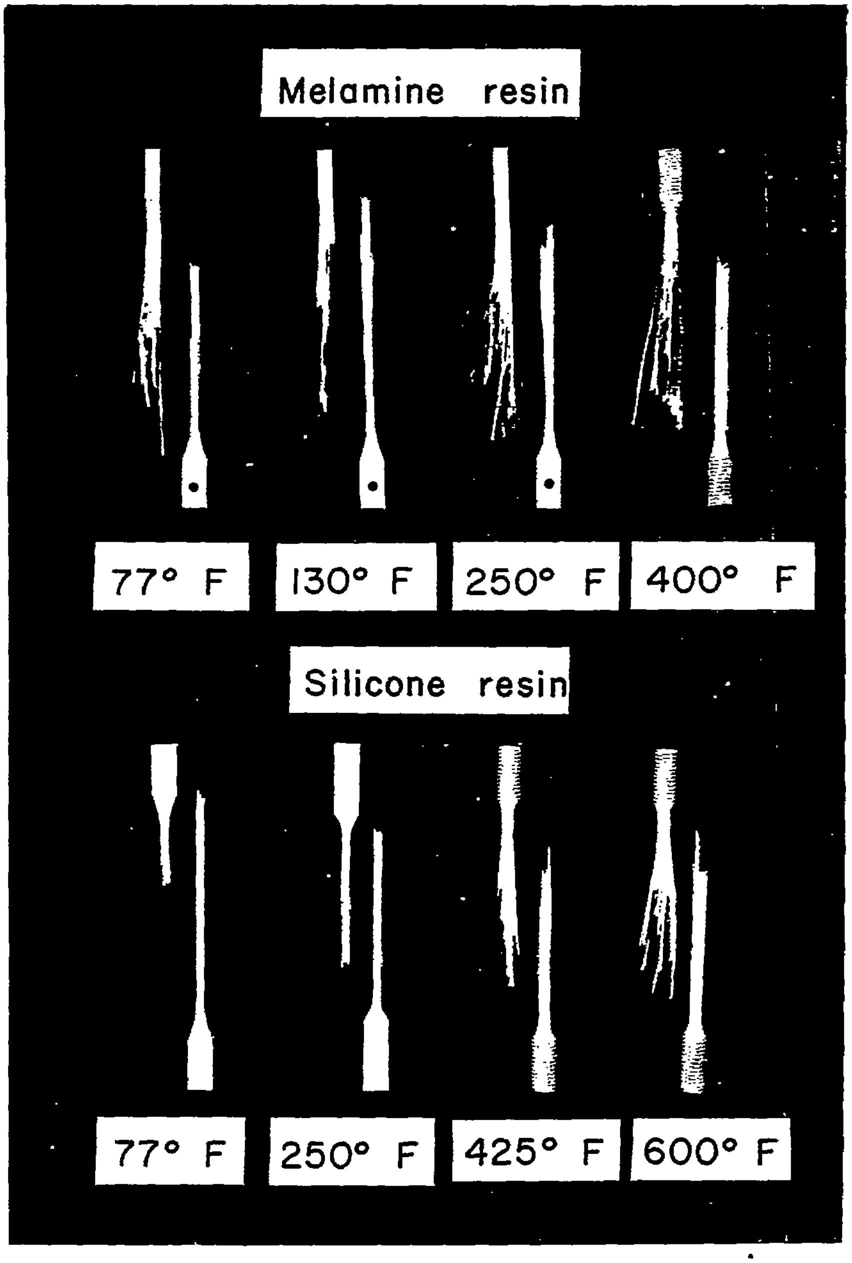
L-89355

Figure 7.- Fractured static-tension specimens for all temperatures.



L-89356

Figure 8.- Fractured static-compression specimens for all temperatures.



L-89357

Figure 9.- Fractured creep and time-to-fracture specimens for all temperatures.

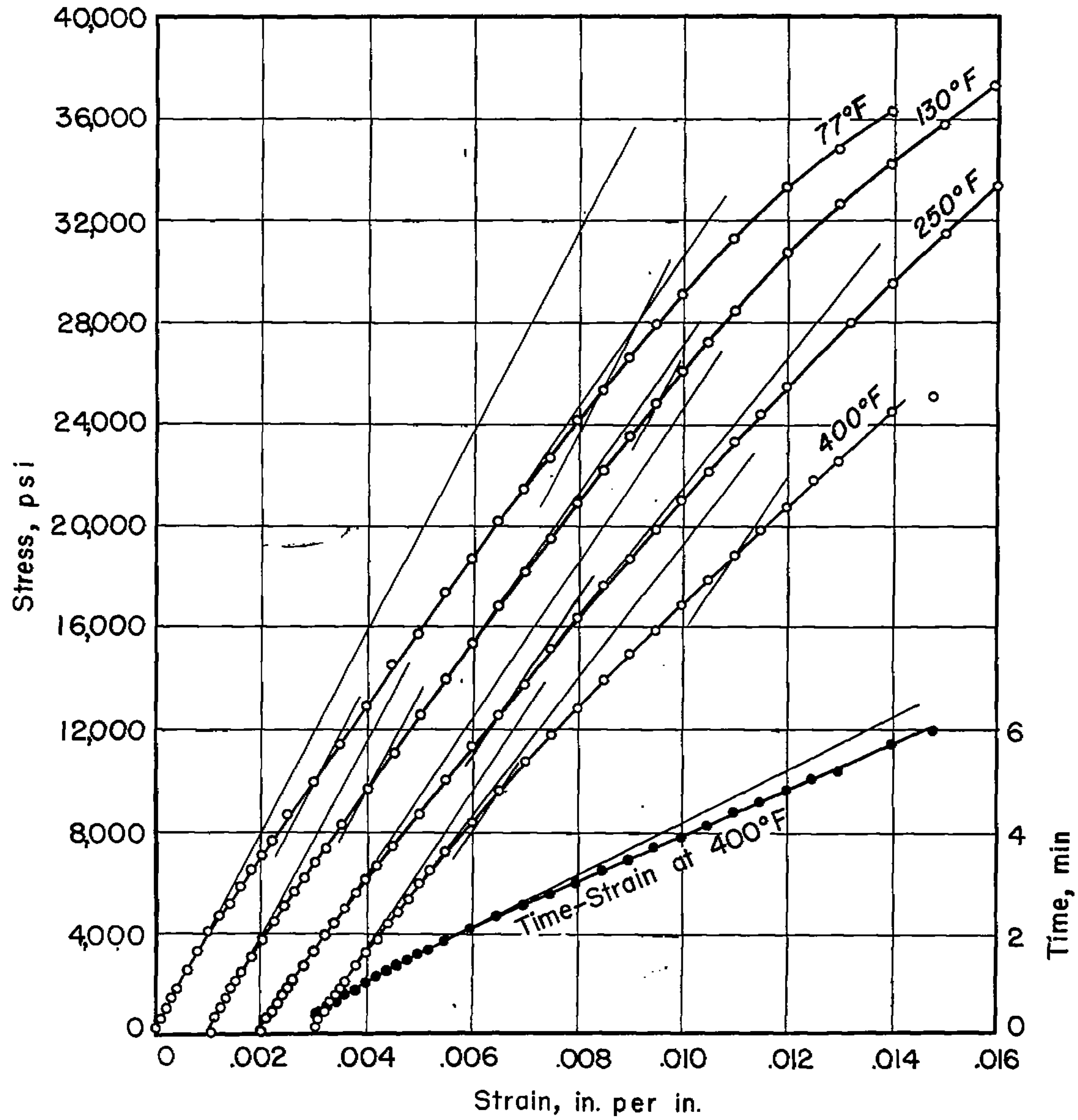


Figure 10.- Representative stress-strain curves for tension tests of a melamine-resin glass-fabric laminate.

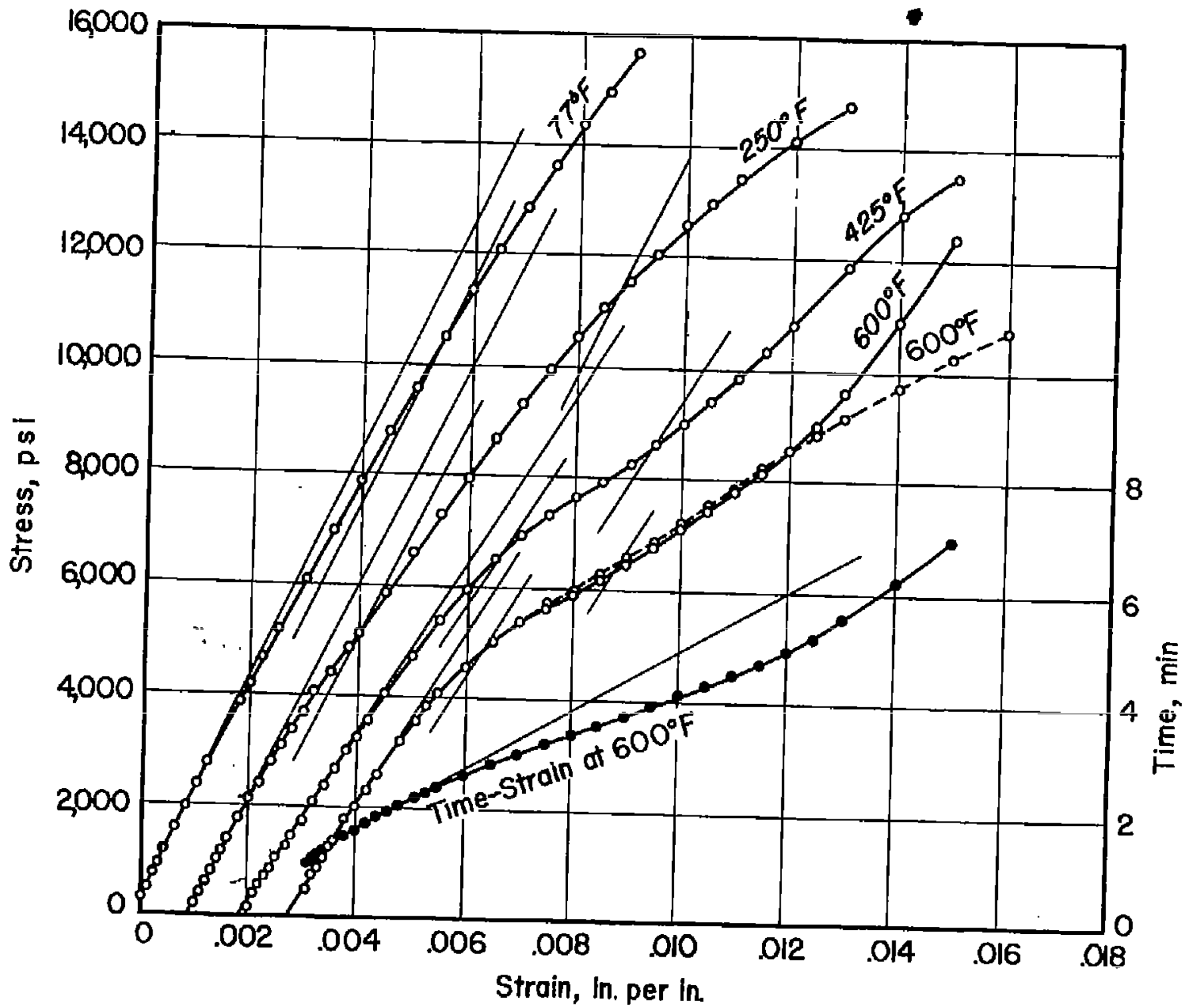


Figure 11.- Representative stress-strain curves for tension tests of a silicone-resin glass-fabric laminate. (See text for explanation of dashed line.)

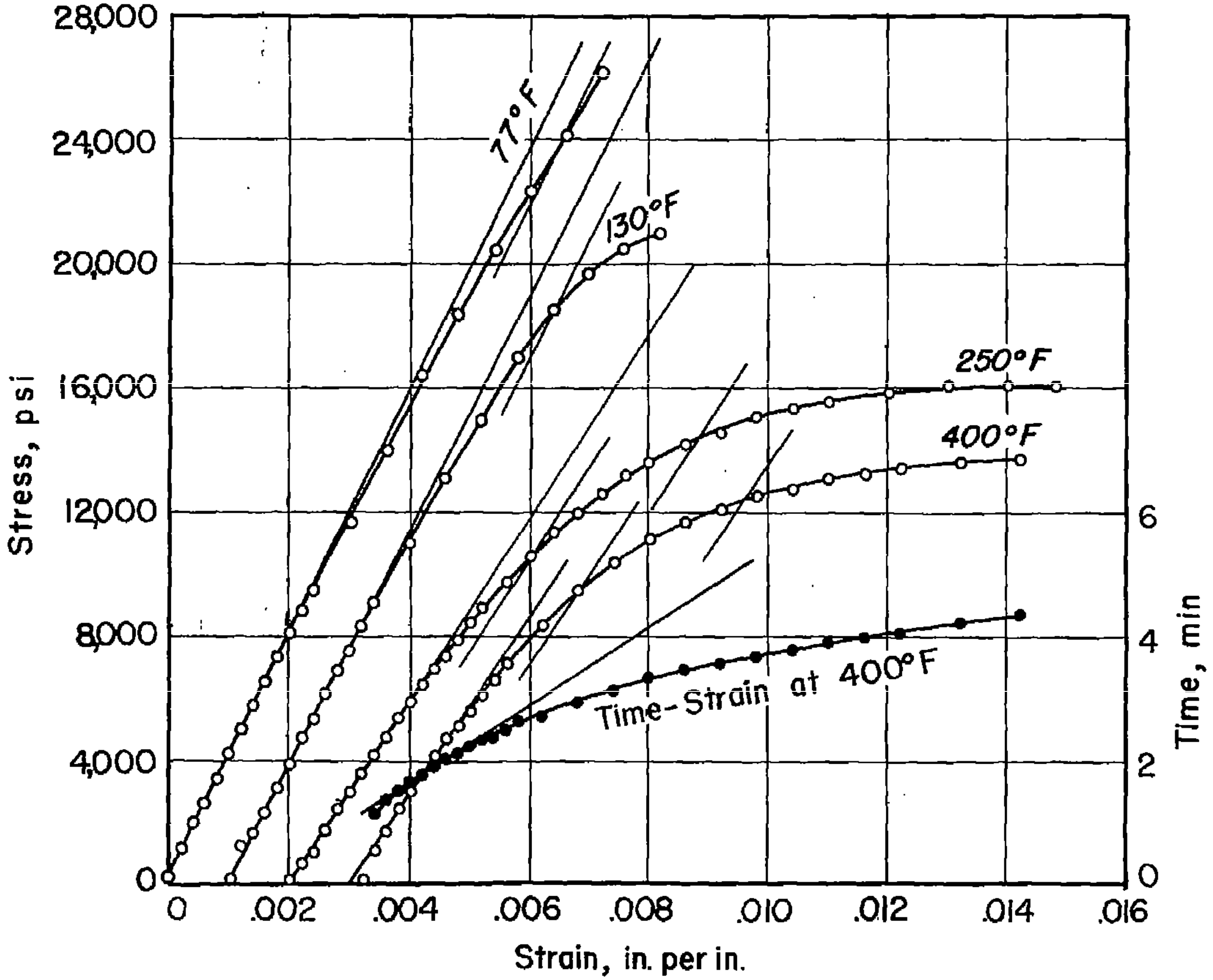


Figure 12.- Representative stress-strain curves for compression tests of a melamine-resin glass-fabric laminate.

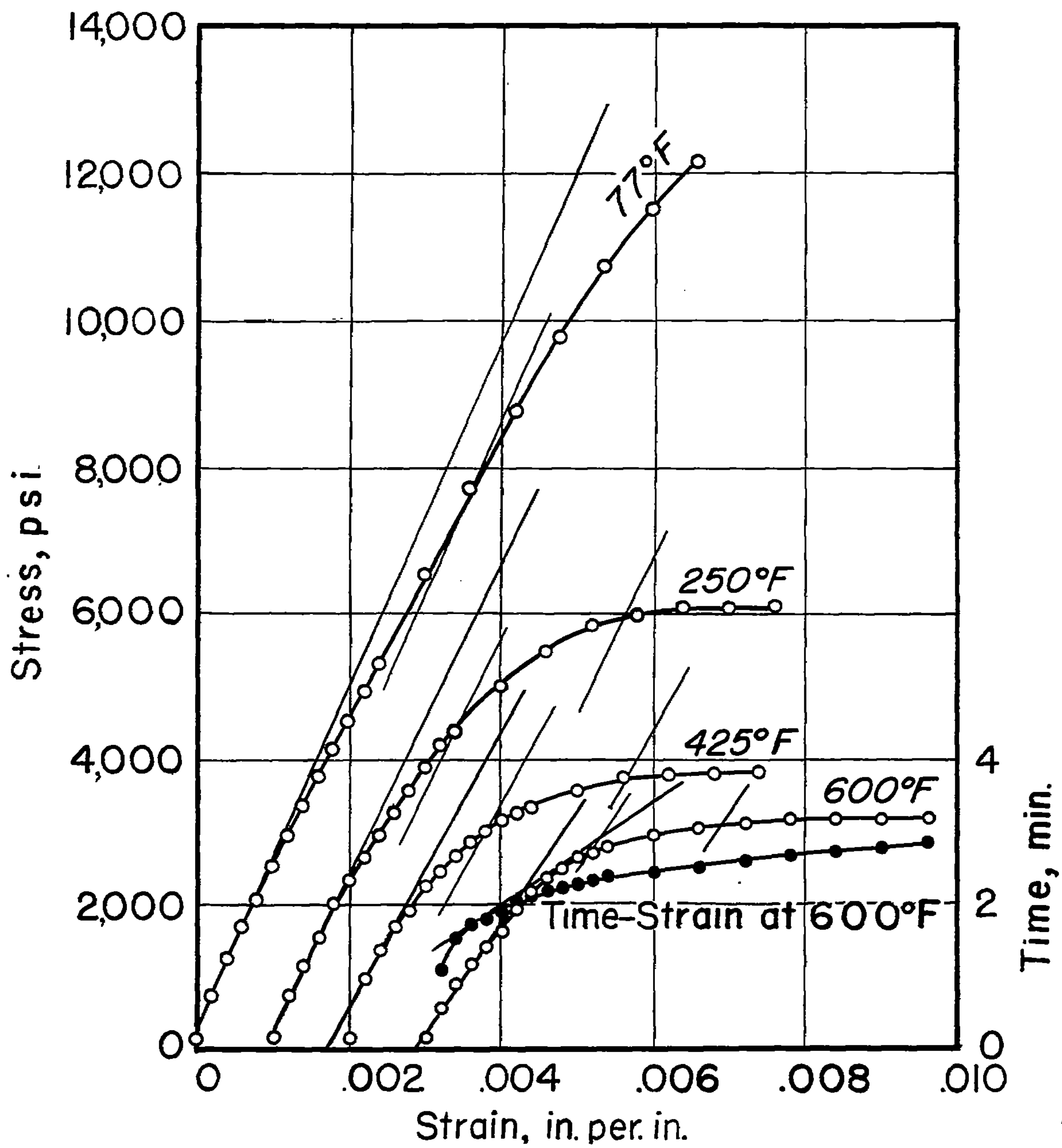


Figure 13.- Representative stress-strain curves for compression tests of a silicone-resin glass-fabric laminate.

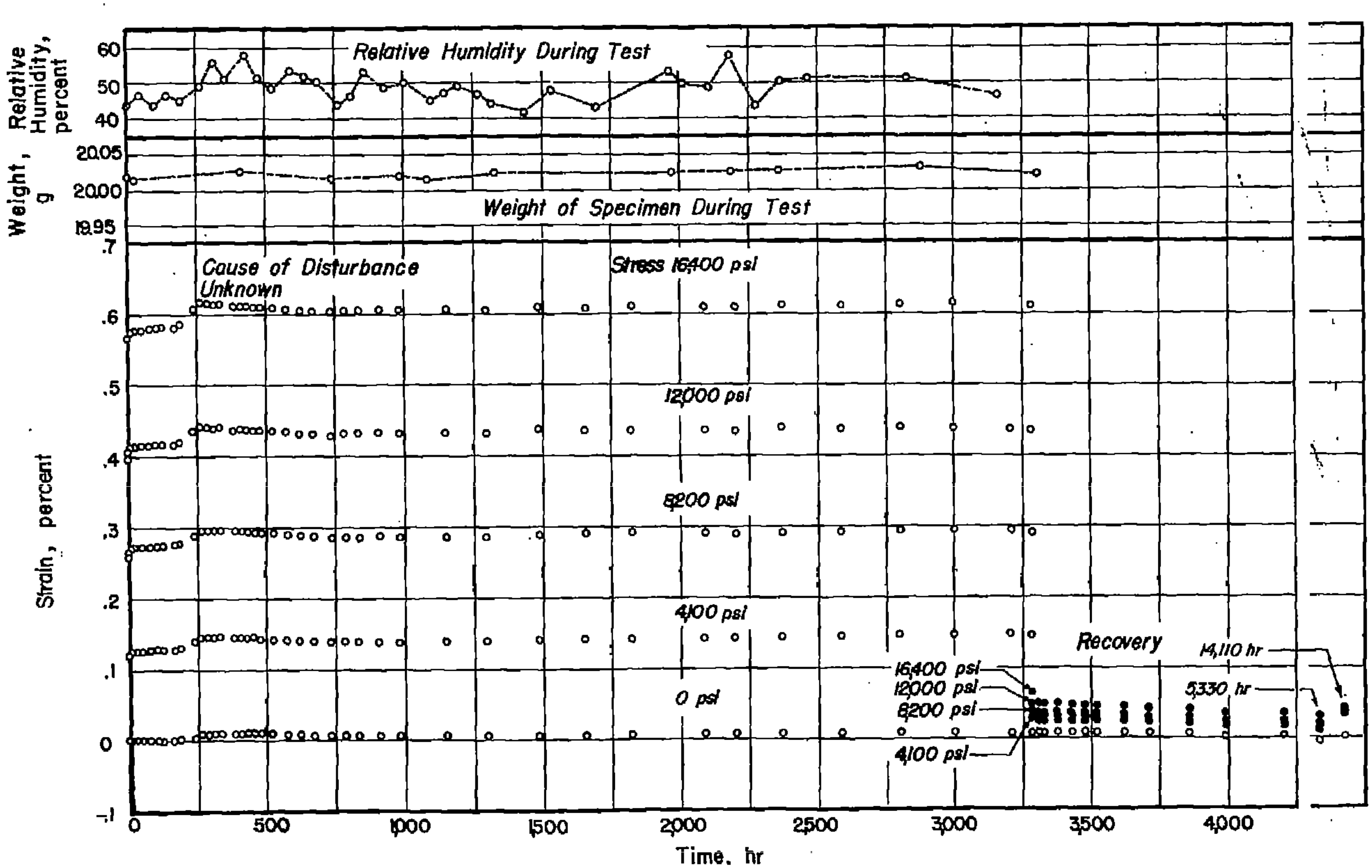


Figure 14.- Creep-time curves for tension creep tests of a melamine-resin glass-fabric laminate tested at 40° F.

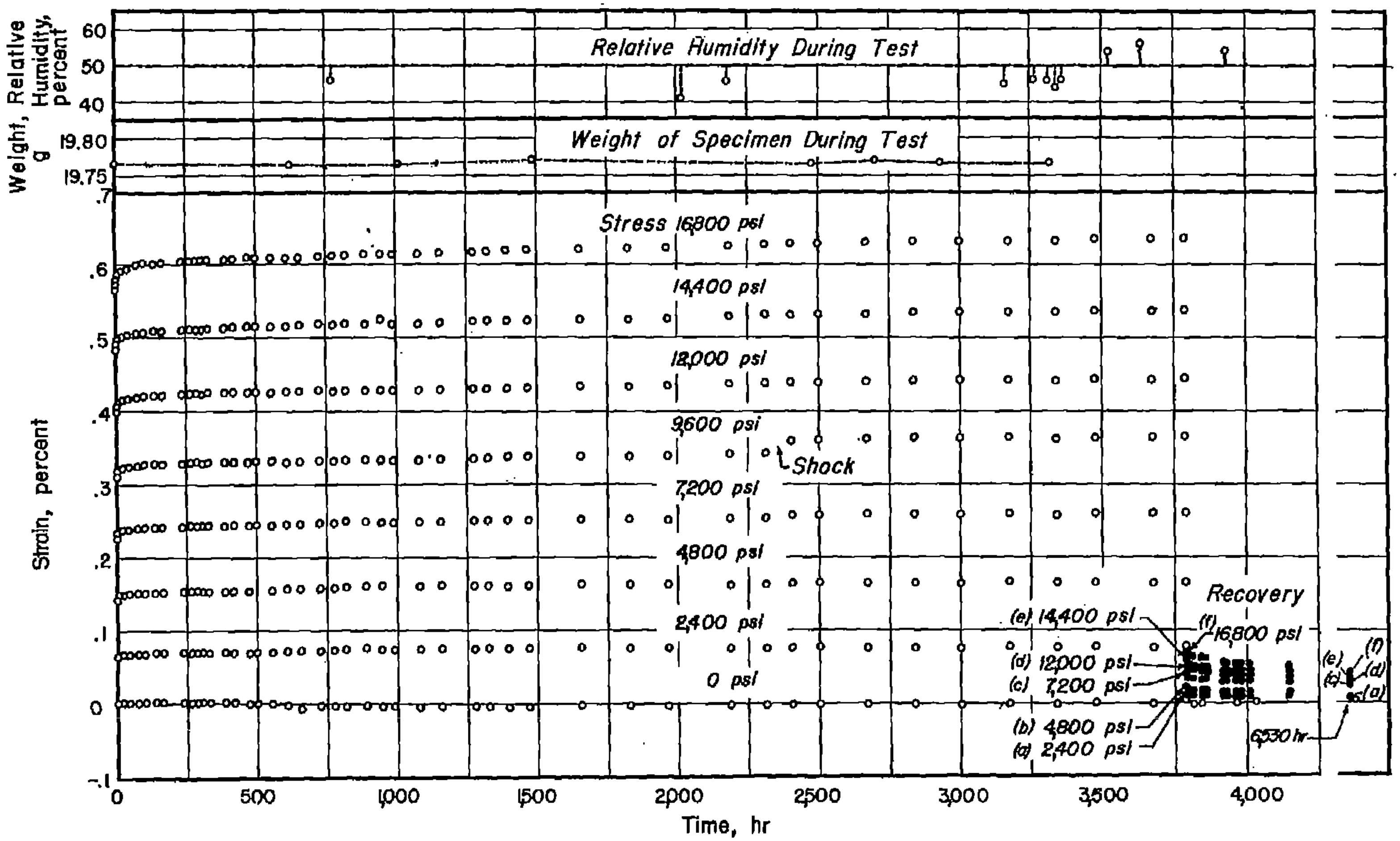


Figure 15.- Creep-time curves for tension creep tests of a melamine-resin glass-fabric laminate tested at 77° F.

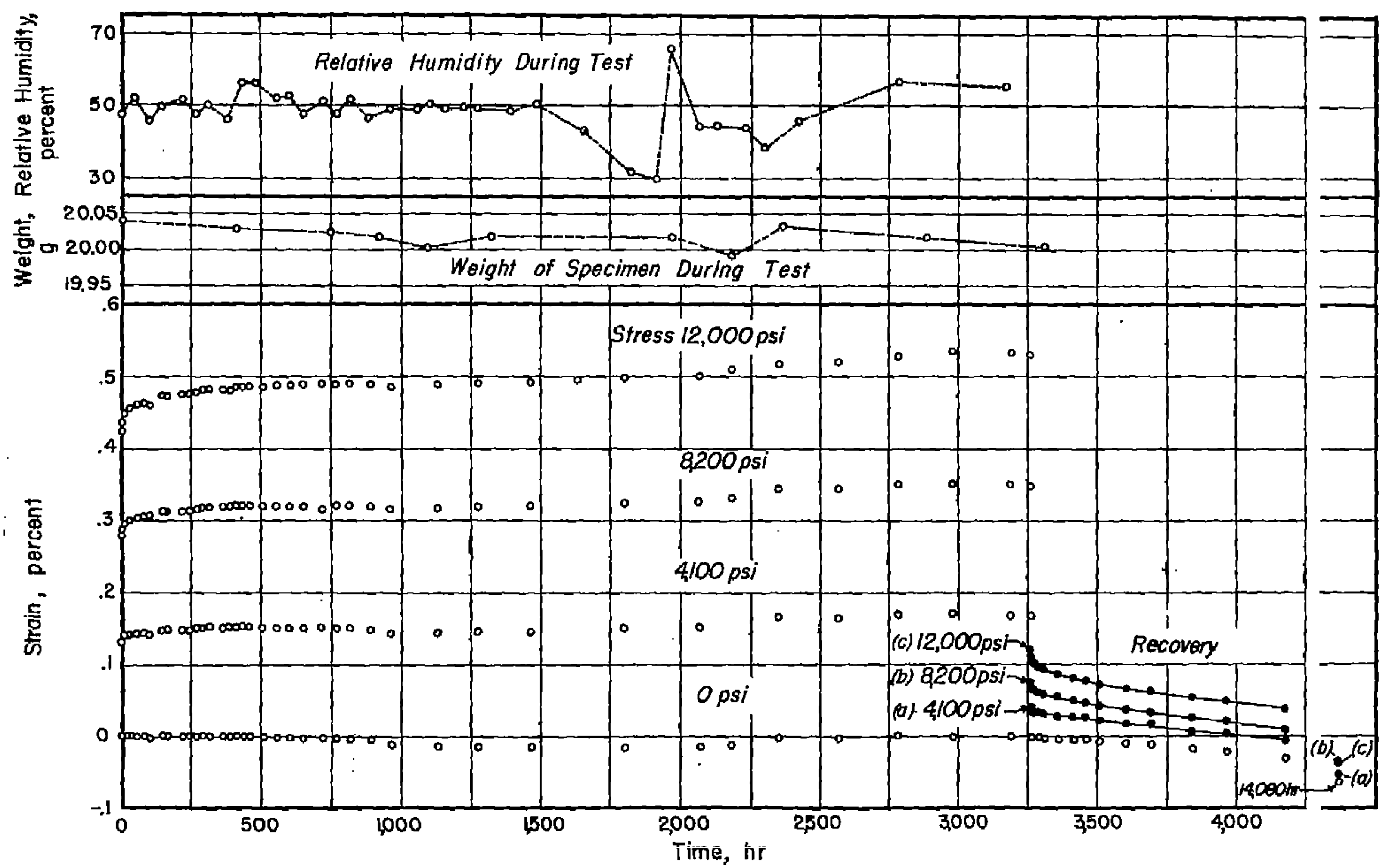


Figure 16.- Creep-time curves for tension creep tests of a melamine-resin glass-fabric laminate tested at 130° F.

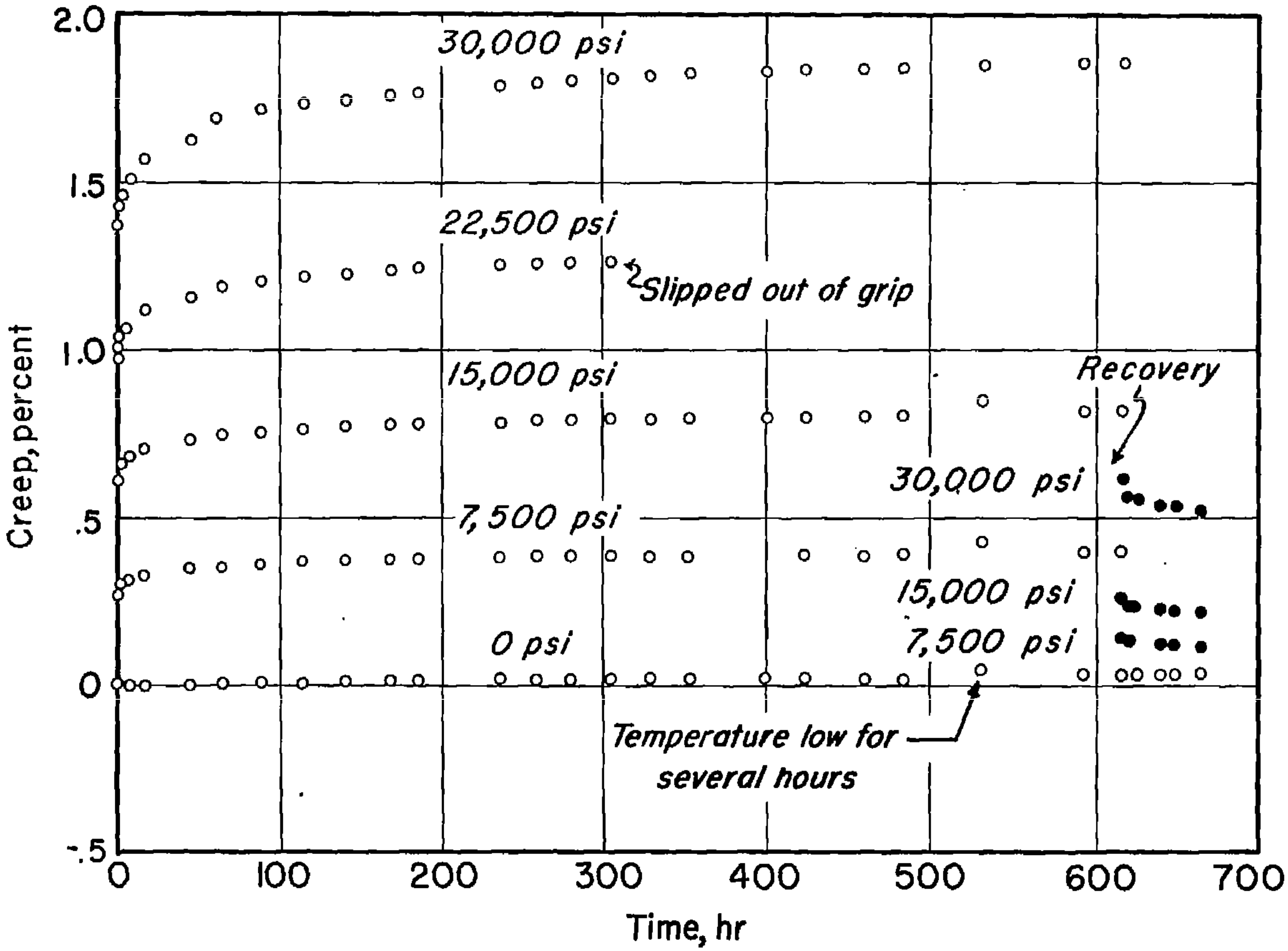


Figure 17.- Creep-time curves for tension creep tests of a melamine-resin glass-fabric laminate tested at 250° F.

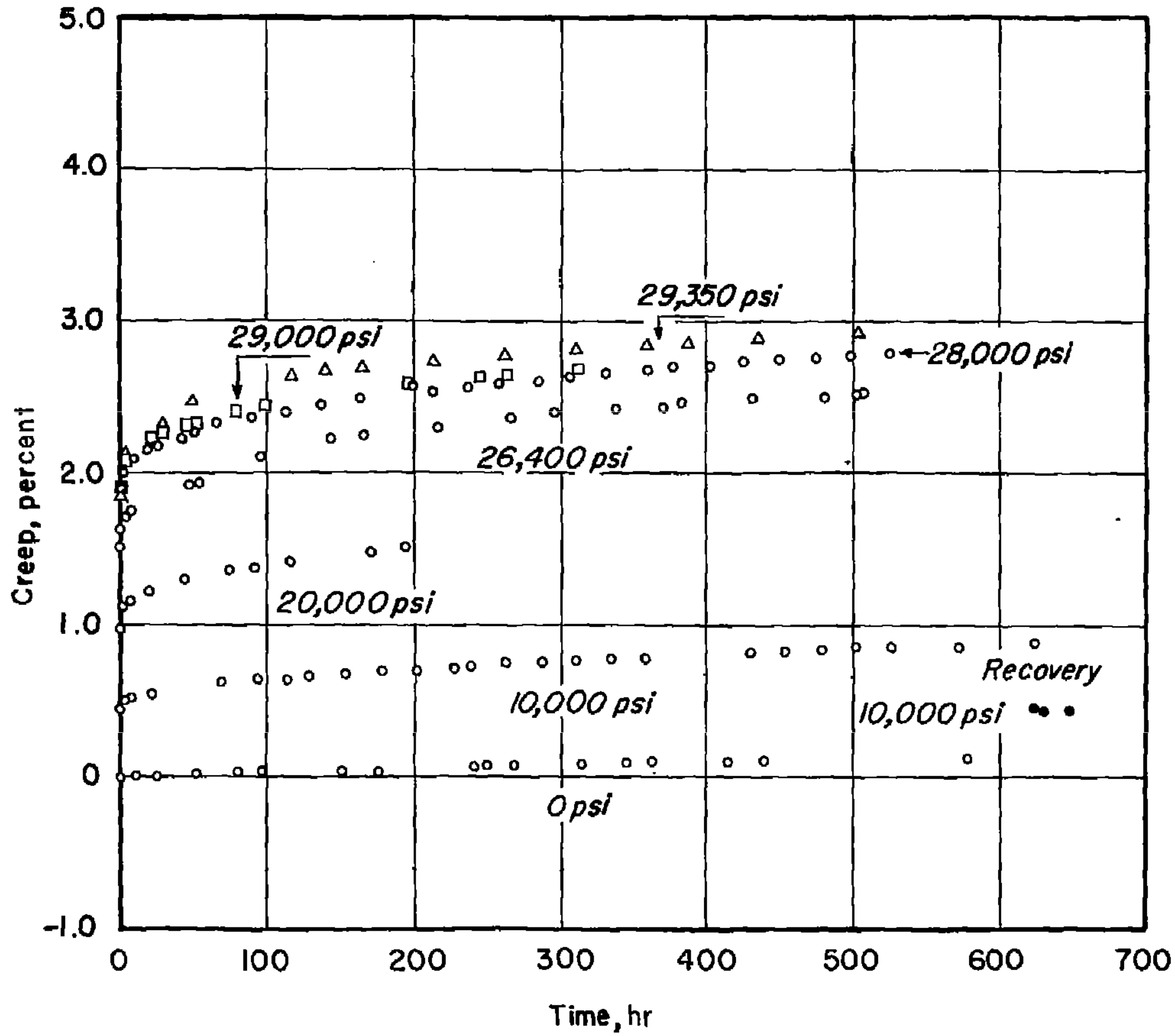
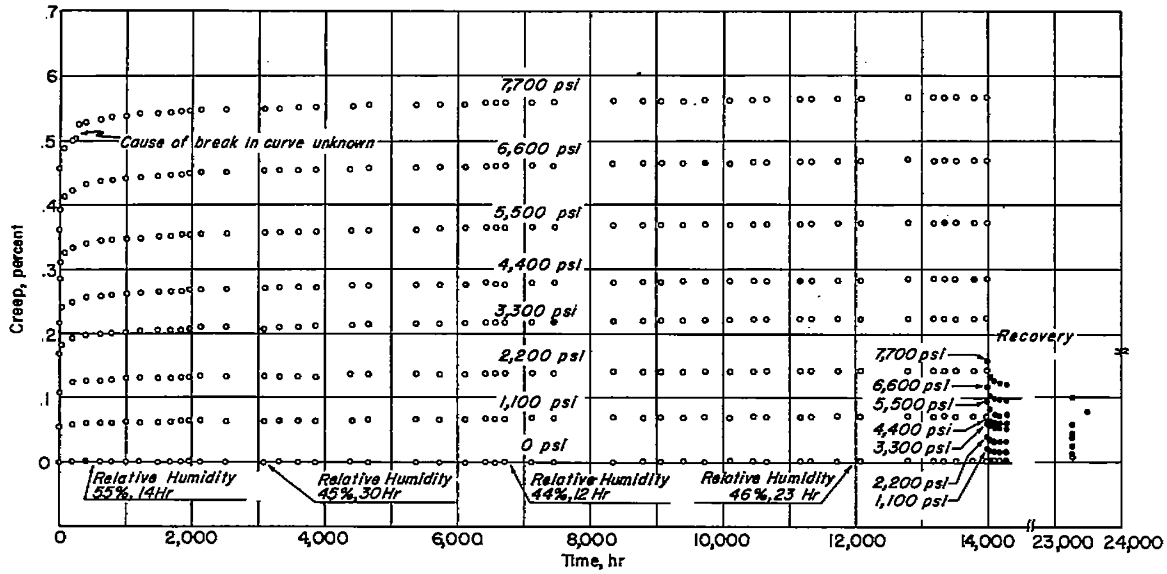
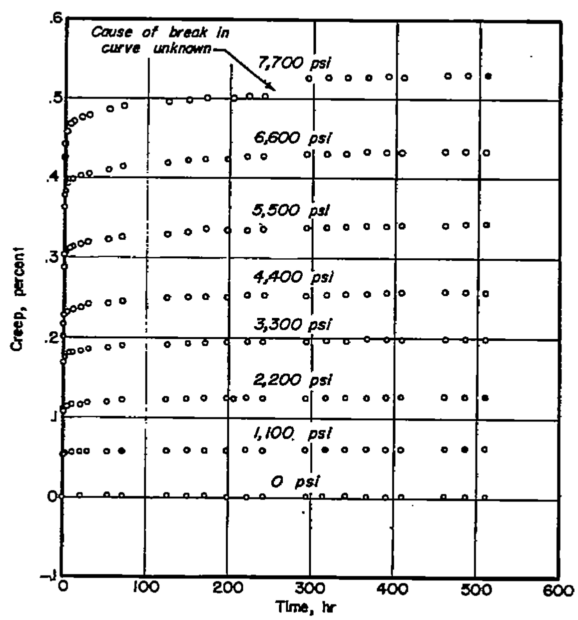


Figure 18.- Creep-time curves for tension creep tests of a melamine-resin glass-fabric laminate tested at 400° F.



(a) 0 to 24,000 hours.



(b) 0 to 600 hours.

Figure 19.- Creep-time curves for tension creep tests of a silicone-resin glass-fabric laminate tested at 77° F and a relative humidity of 50 percent, unless otherwise noted.

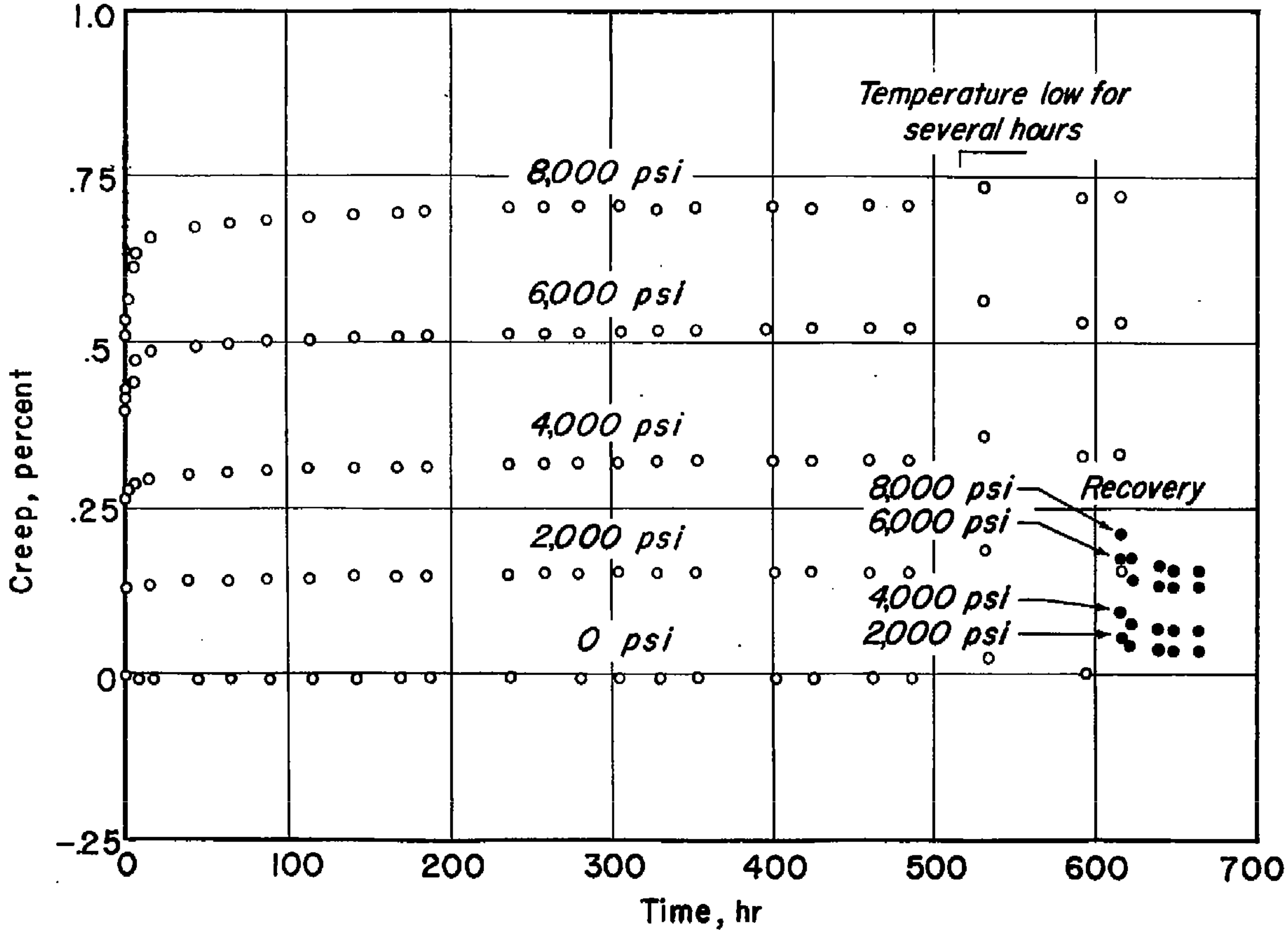


Figure 20.- Creep-time curves for tension creep tests of a silicone-resin glass-fabric laminate tested at 250° F.

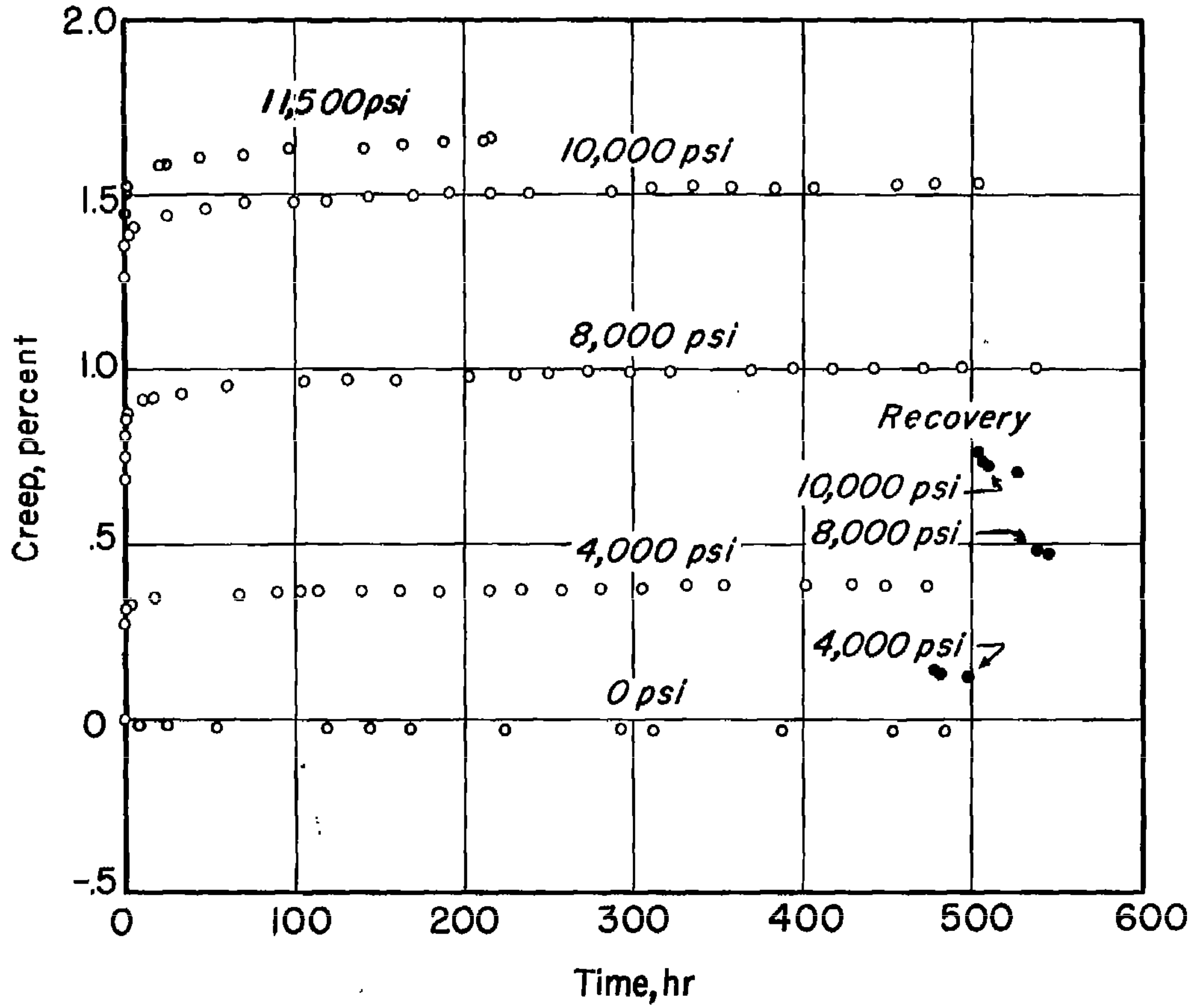


Figure 21.- Creep-time curves for tension creep tests of a silicone-resin glass-fabric laminate tested at 425° F.

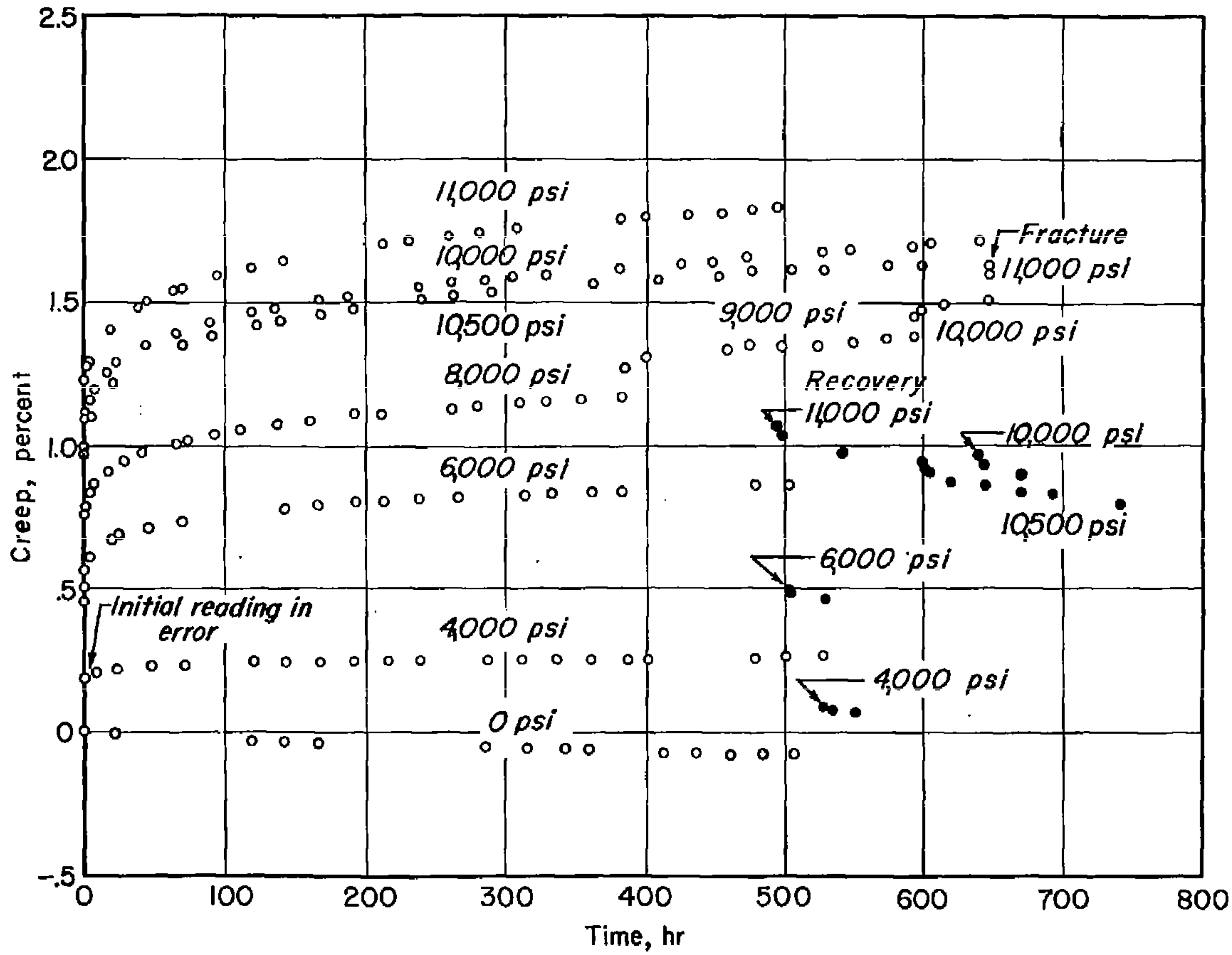


Figure 22.- Creep-time curves for tension creep tests of a silicone-resin glass-fabric laminate tested at 600° F.

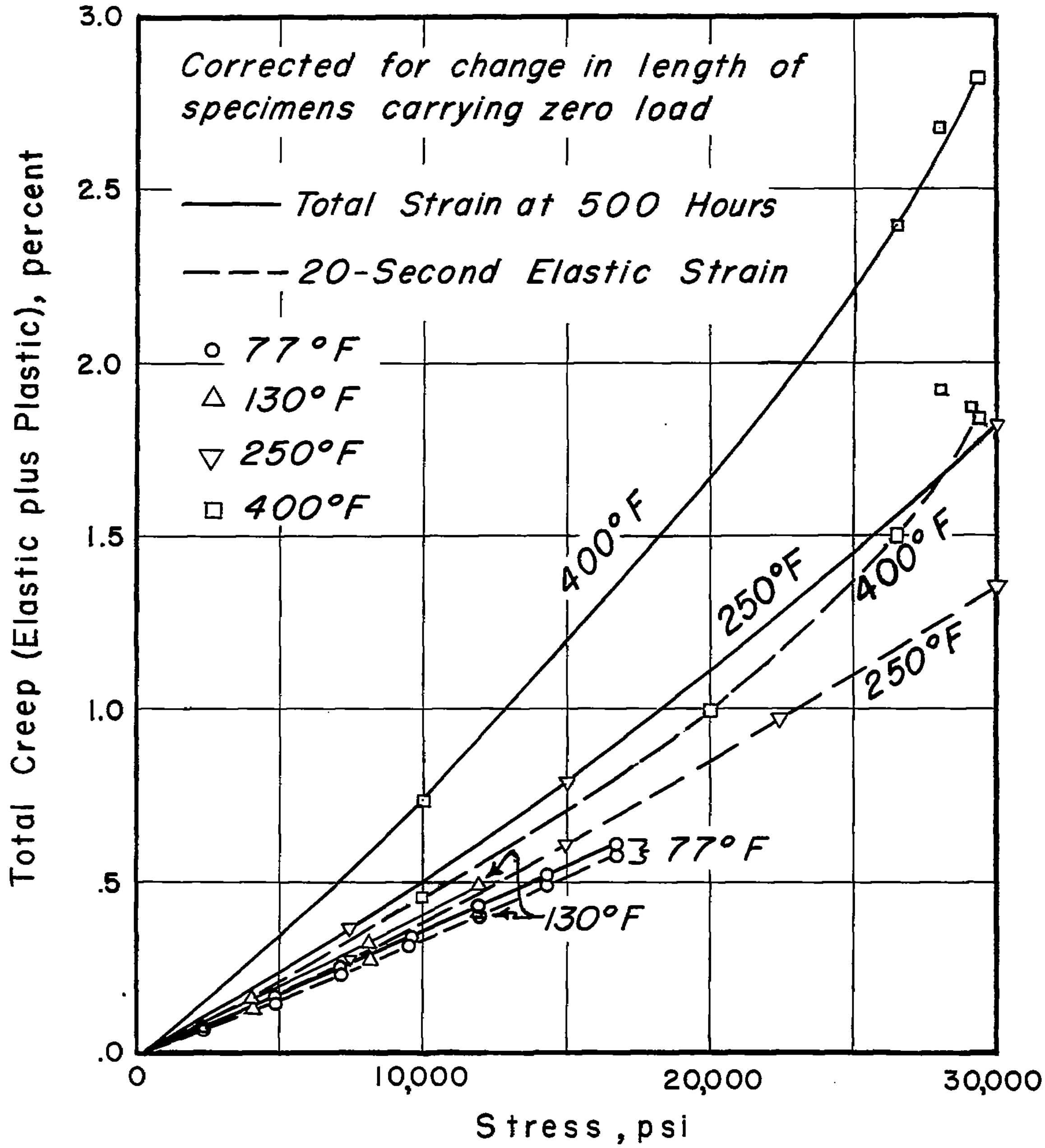


Figure 23.- Effect of stress on 20-second elastic strain and on total creep at 500 hours at various temperatures for a melamine-resin glass-fabric laminate. Data corrected for change in length of specimen carrying zero load.

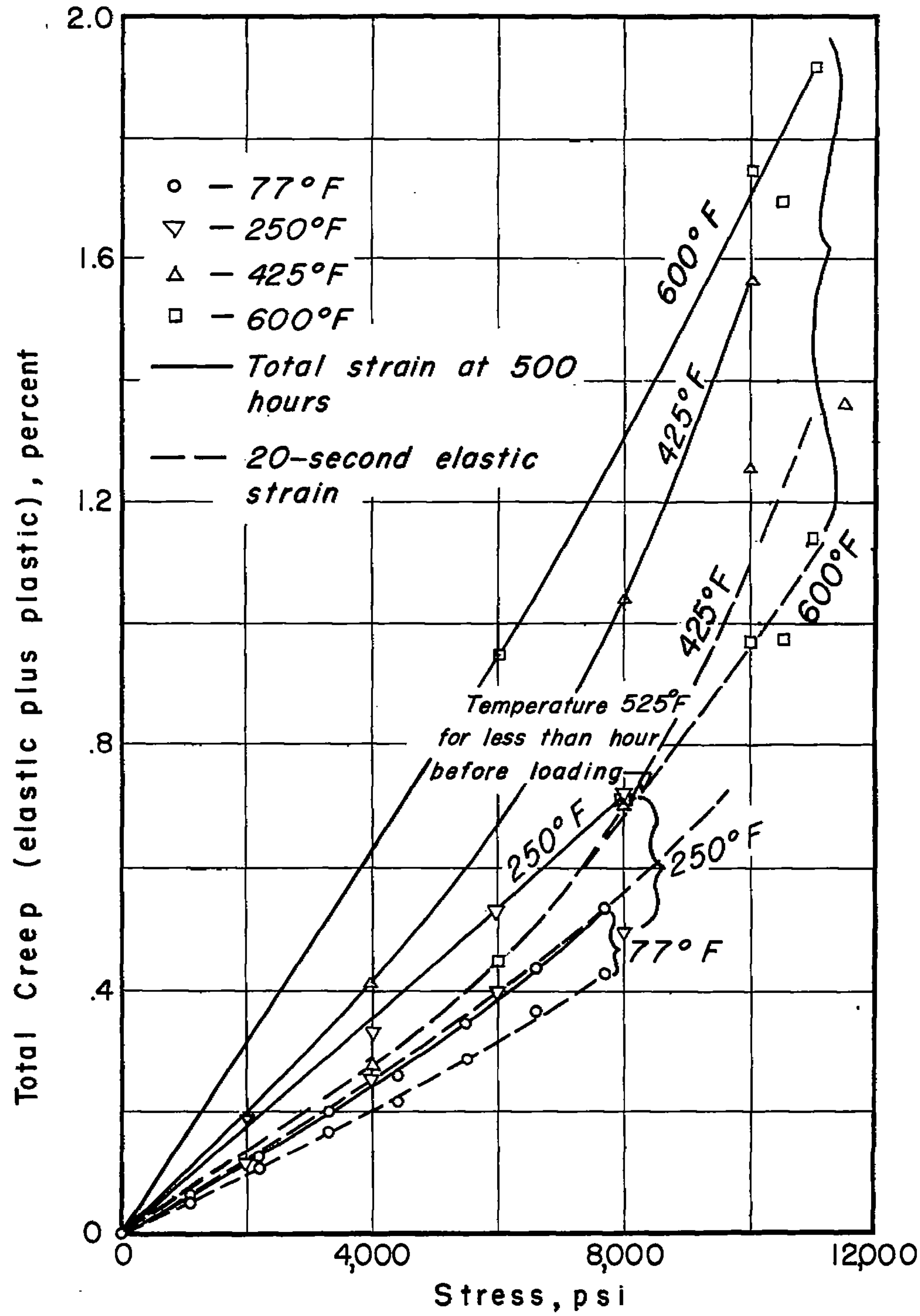


Figure 24.- Effect of stress on 20-second elastic strain and on total creep at 500 hours at various temperatures for a silicone-resin glass-fabric laminate. Data corrected for change in length of specimen carrying zero load.

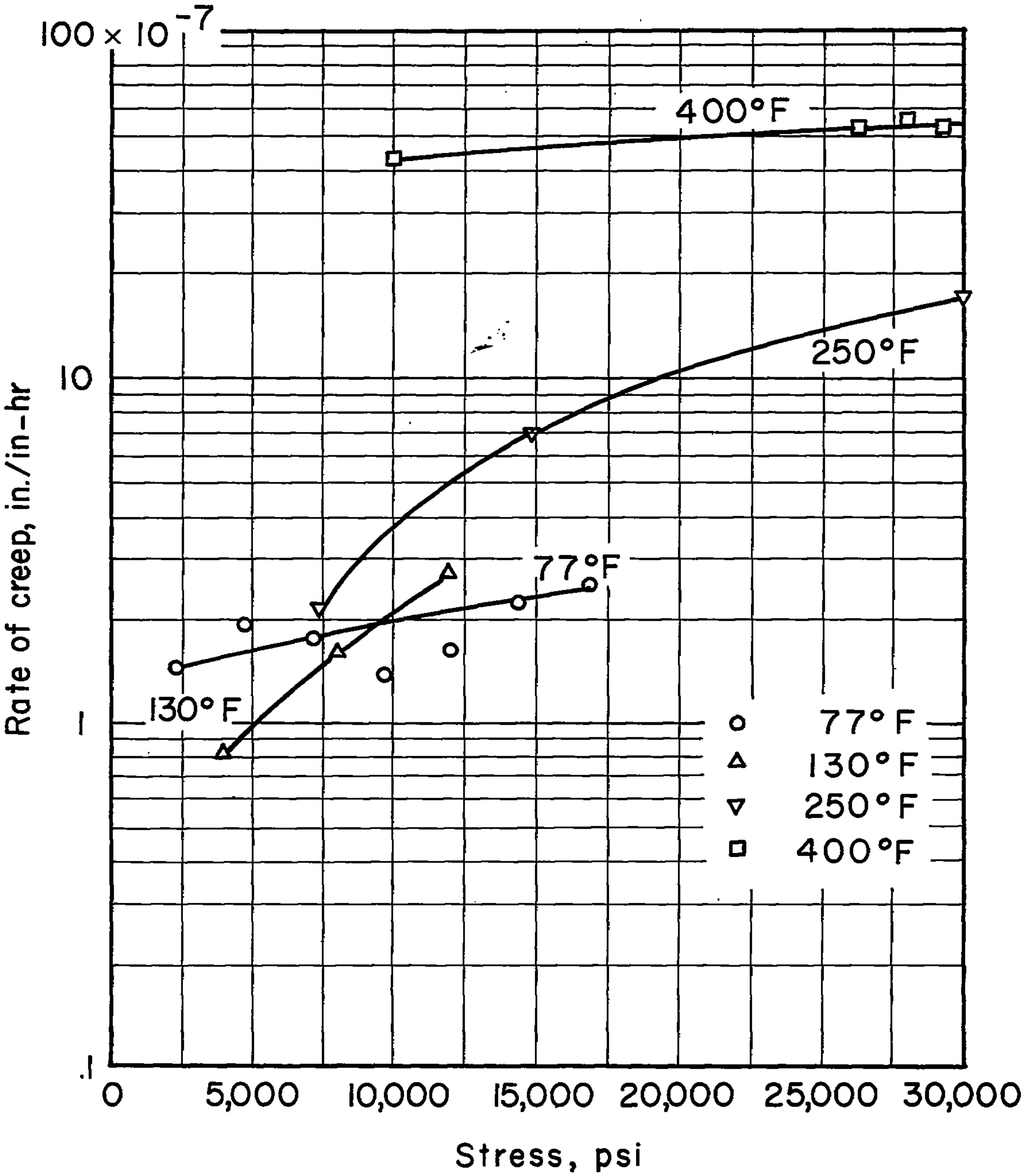


Figure 25.- Rate of creep at 500 hours versus stress at various temperatures for a melamine-resin glass-fabric laminate. Data corrected for change in length of specimen carrying zero load.

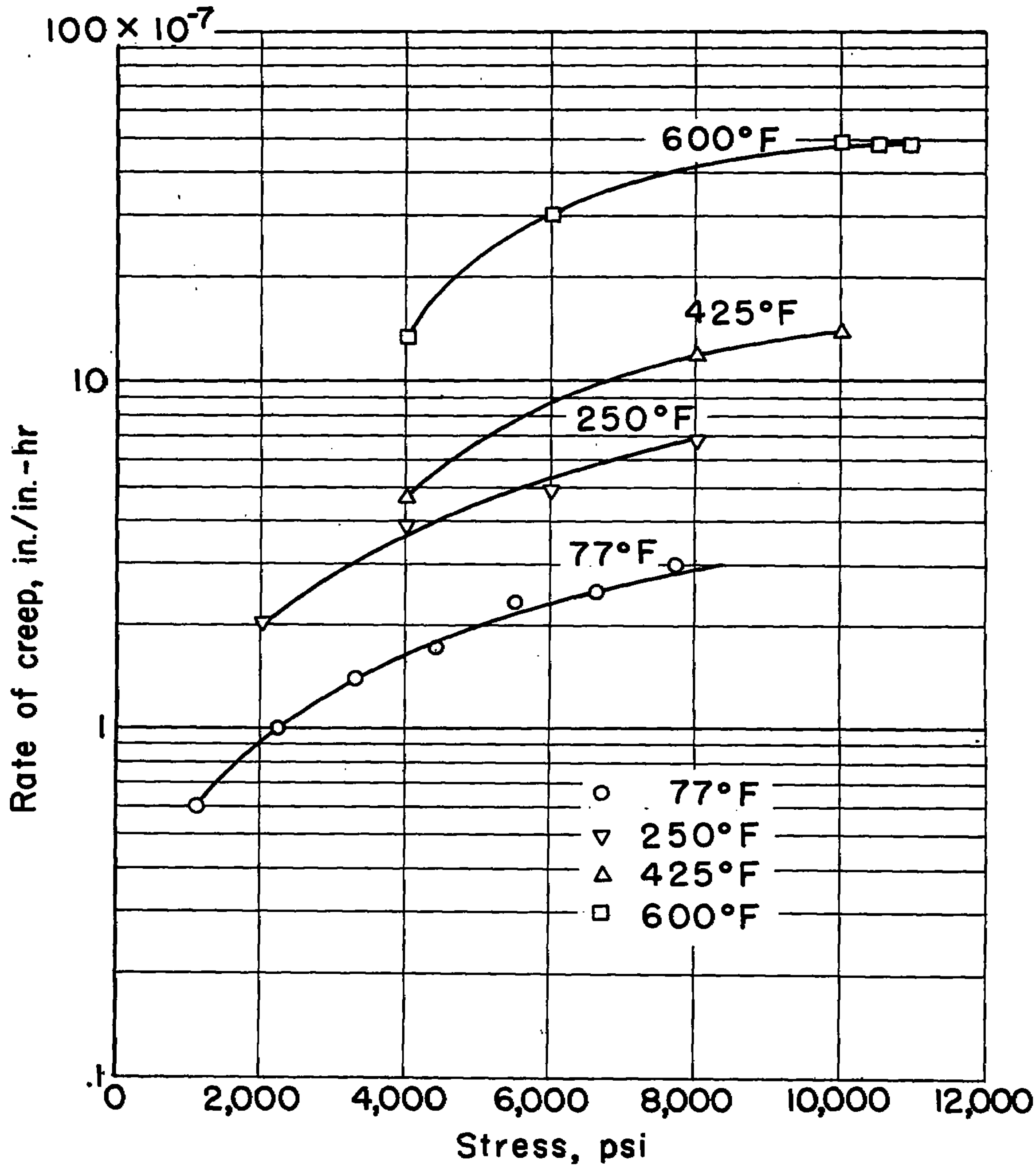


Figure 26.- Rate of creep at 500 hours versus stress at various temperatures for a silicone-resin glass-fabric laminate. Data corrected for shrinkage.

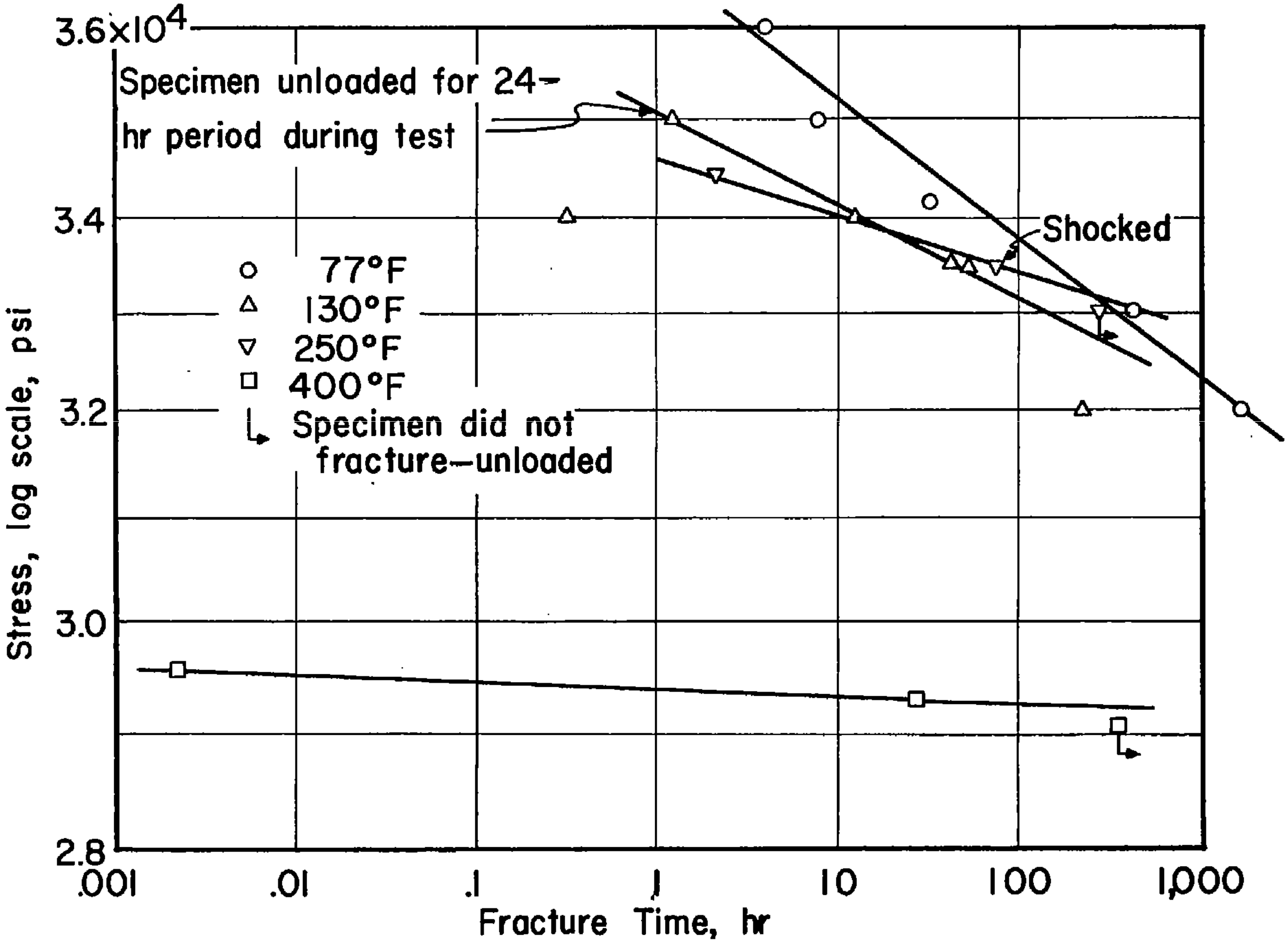


Figure 27.- Stress versus time to fracture at various temperatures for a melamine-resin glass-fabric laminate.

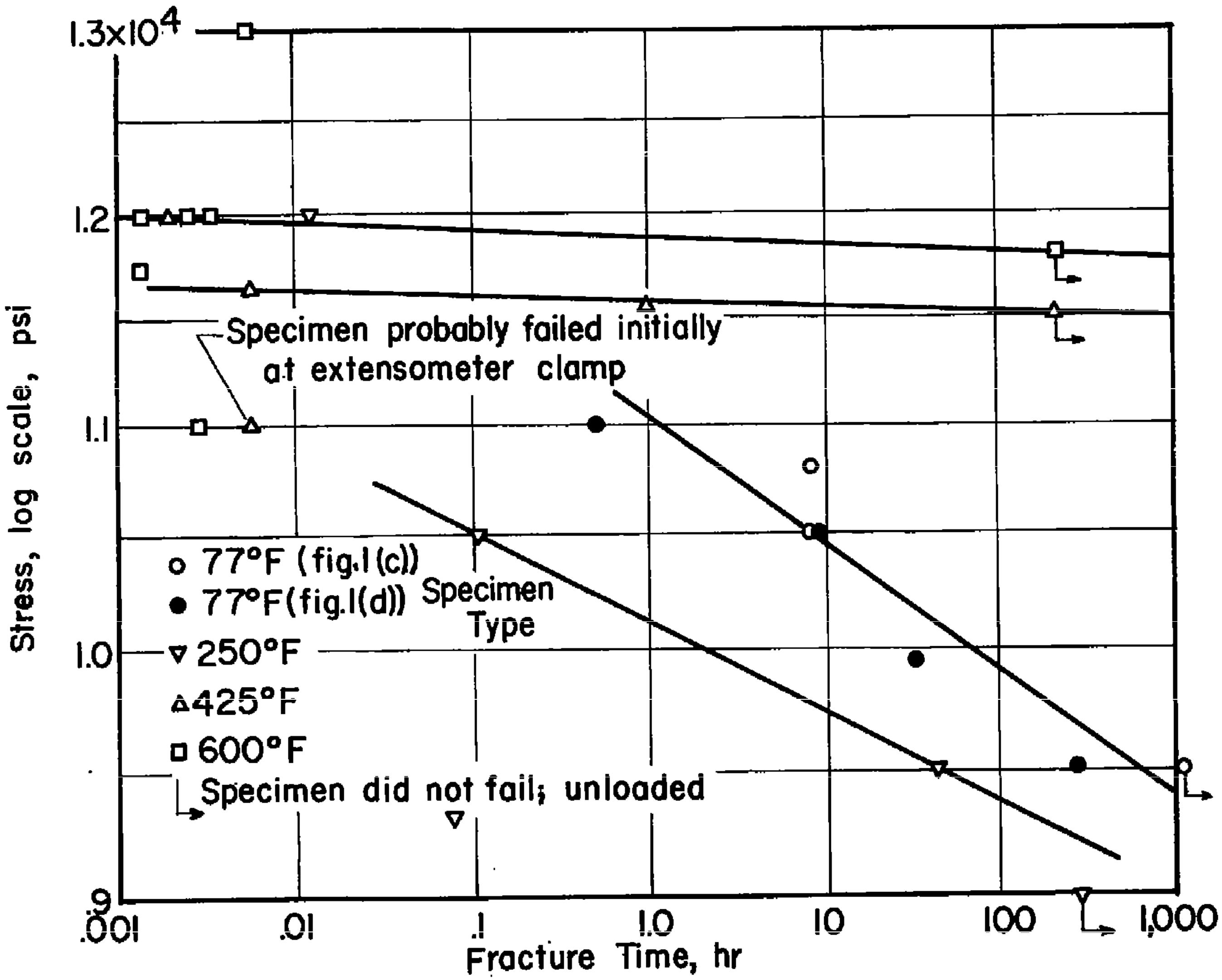


Figure 28.- Stress versus time to fracture at various temperatures for a silicone-resin glass-fabric laminate.

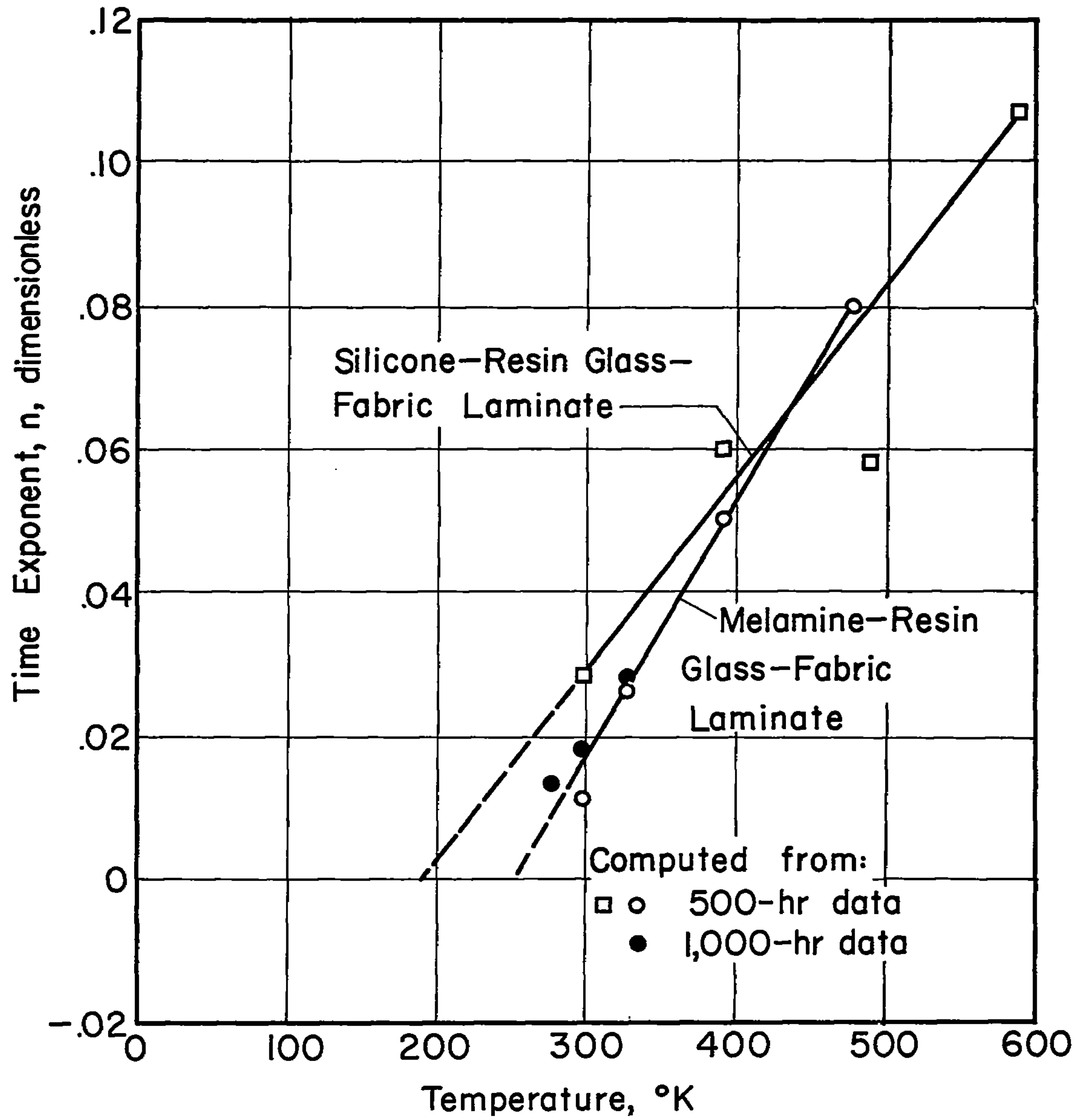


Figure 29.- Time exponent versus absolute temperature for melamine-resin and silicone-resin glass-fabric laminates.

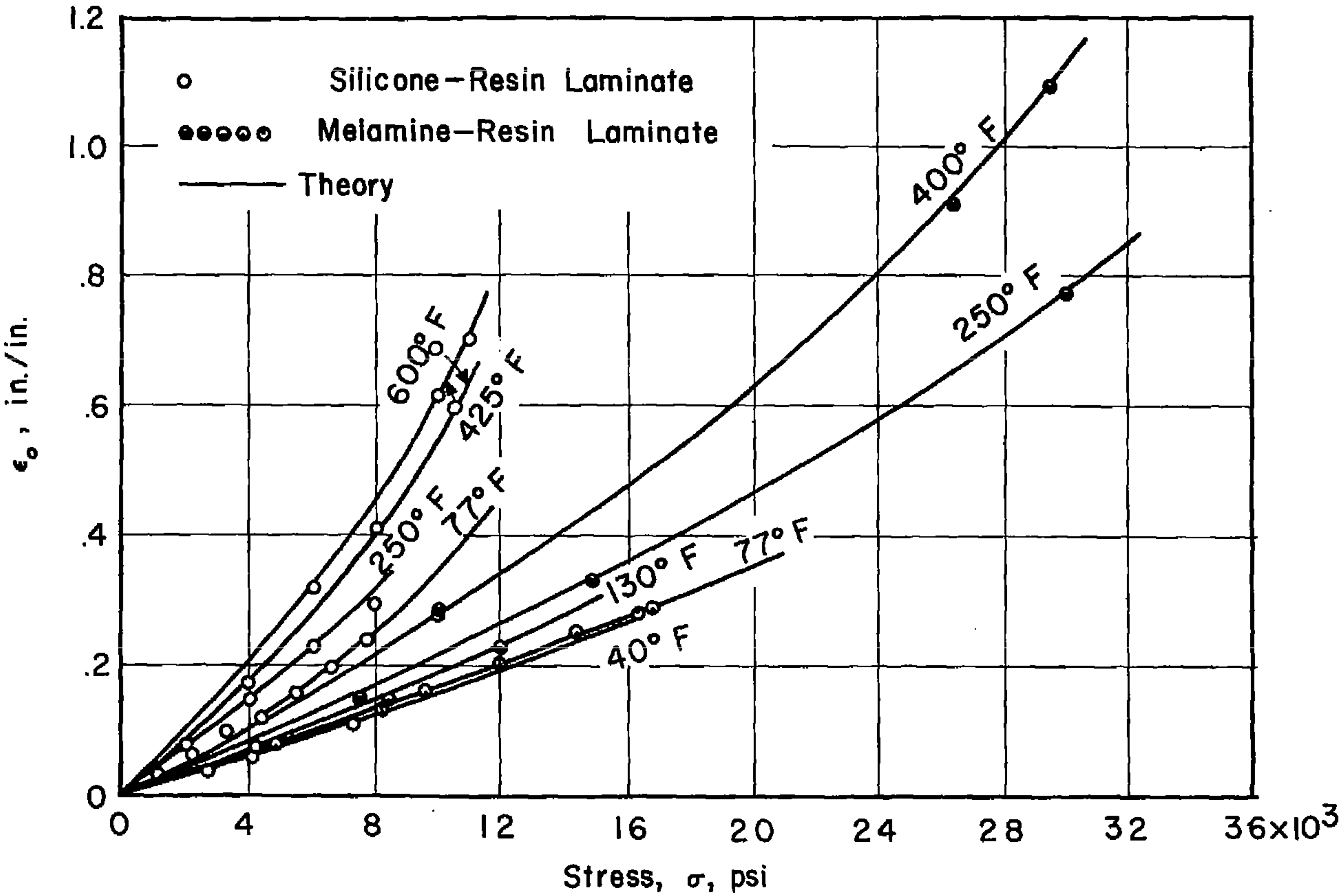


Figure 30.- Effect of stress on time-independent term ϵ_o.

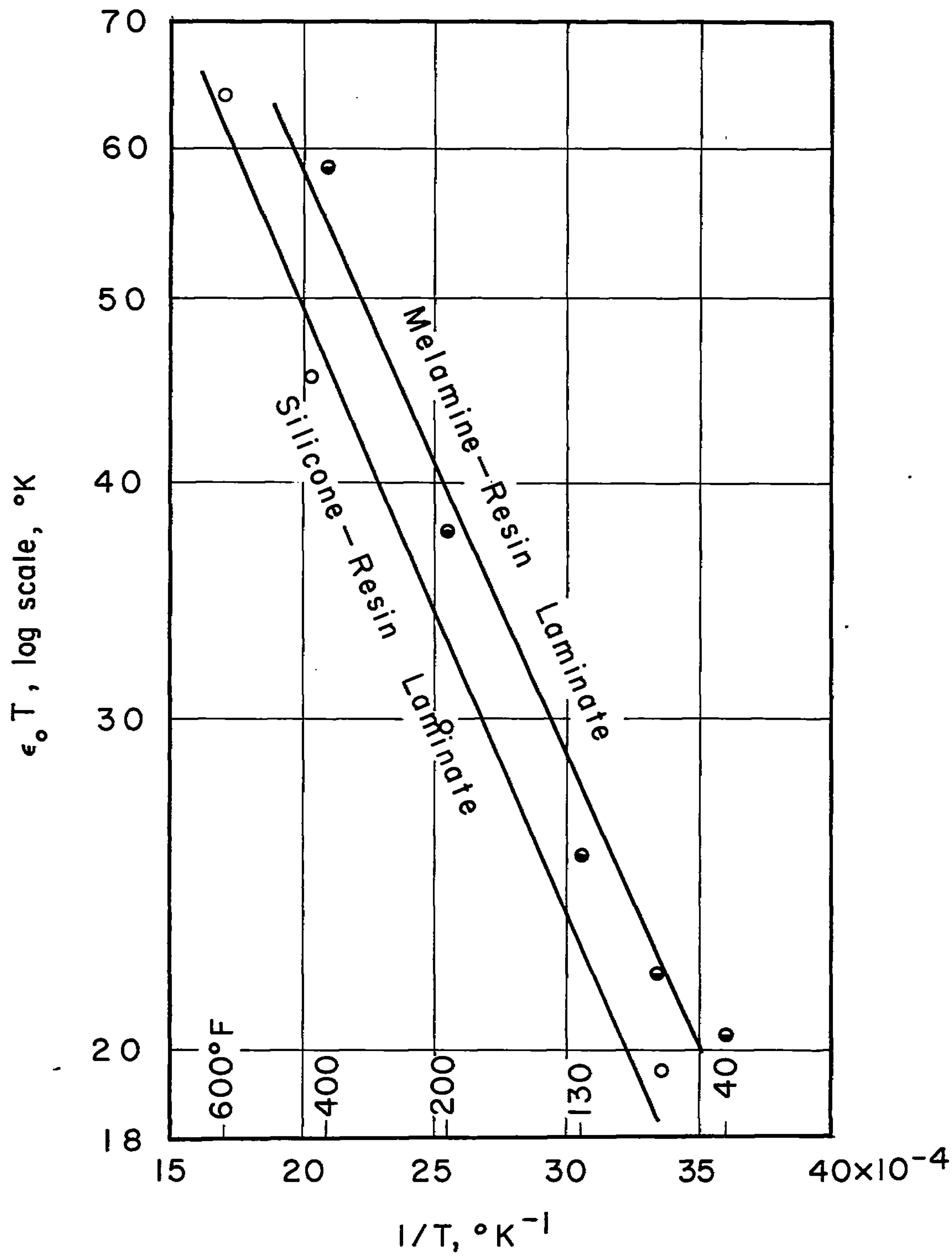


Figure 31.- Relation between $\epsilon_o T$ and $1/T$ (see eq. (14)).